Calhoun
Institutional Archive of the Naval Postgraduate School

Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

1965

Correlation of ship position reports gathered by simulated ocean surveillance satellites

McArthur, Robert R.; Slankard, Max L.

Monterey, California: U.S. Naval Postgraduate School

http://hdl.handle.net/10945/11876

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun

DUDLEY KNOX LIBRARY

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

NPS ARCHIVE
1965
MCARTHUR, R.

CORRELATION OF SHIP POSITION REPORTS GATHERED BY SIMULATED OCEAN SURVEILLANCE SATELLITES

ROBERT R. McARTHUR
and
MAX L. SLANKARD

[illegible]
U.S. N[illegible]
M[illegible] A

4

CORRELATION OF SHIP POSITION REPORTS GATHERED BY SIMULATED OCEAN SURVEILLANCE SATELLITES

* * * * *

Robert R. McArthur

and

Max L. Slankard

CORRELATION OF SHIP POSITION REPORTS GATHERED BY SIMULATED OCEAN SURVEILLANCE SATELLITES

by

Robert R. McArthur

Lieutenant Commander, United States Navy

and

Max L. Slankard

Commander, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
OPERATIONS RESEARCH

United States Naval Postgraduate School
Monterey, California

1965

NPS ARCHIVE
1965
MCARTHUR, R.

[illegible]

Library
U. S. Naval Postgraduate School
Monterey, California

CORRELATION OF SHIP POSITION REPORTS GATHERED BY SIMULATED OCEAN SURVEILLANCE SATELLITES

by

Robert R. McArthur

and

Max L. Slankard

This work is accepted as fulfilling
the thesis requirements for the degree of
MASTER OF SCIENCE
IN
OPERATIONS RESEARCH
from the
United States Naval Postgraduate School

ABSTRACT

Two models for the correlation of ship position reports obtained and relayed by ocean surveillance satellites are described. The models are intended to process position reports of ships detected by satellites and correlate this data to provide intelligence concerning the position, course, and speed of ships traversing the ocean surface. A probabilistic model assigns position report correlations by reliance on probabilities assigned to computed ship speed and to changes of course and speed. A reliability factor is determined for each track. The deterministic model avoids explicit use of probability theory and correlates position reports on the basis of proximity of the position report to a position predicted by track extension. Evaluation of the models by means of computer simulations is described. Results of the evaluation are discussed and recommendations are made concerning areas for further investigation. The computer programs are included in the Appendicies.

TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	General Analysis	3
3.	The Deterministic Correlation Model	10
4.	The Probabilistic Correlation Model	26
5.	Conclusions and Recommendations	51
6.	Bibliography	53
	Appendix I - FORTRAN 63 Program - Deterministic Model	54
	Appendix II - Input and Output - Deterministic Model	81
	Appendix III - FORTRAN 63 Program - Probabilistic Model	87
	Appendix IV - Flow Charts - Probabilistic Model	121

LIST OF ILLUSTRATIONS

Figure Page

1. Illustration of Possible Tracks for a Given Situation 5
2. Illustration of One of the Basic Principles of the Deterministic Correlation Model Logic 14
3. Diagram of Track Initiation and Extension 17
4. Definition of Area Constructed Around Projected Position 21
5. Summary of Test Simulations for Deterministic Model 24
6. Initial Tentative Tracks 38
7. Most Likely Tracks 39
8. Tentative Extensions of Most Likely Tracks 40
9. Firm Track Established 41
10. Track Split 42
11. New Track Initiated by Track Splitting 43
12. Chart of Test Situation for Probabilistic Model 45
13. Table of Test Results 46
14. Sample Output for TRACK IV 92

1. Introduction

Since the first sputnik was successfully projected into orbit in 1957, the possibility of using a satellite for reconnaissance and surveillance of the oceans has been of increasing interest to military men. Studies have been conducted to analyze the usefulness and feasibility of a surveillance satellite system and several reports have proposed system requirements. A report by the Pacific Missile Range described some of the problems to be encountered in processing data received from a surveillance satellite. [1]

During the spring and summer of 1964, analysts at the Advanced Programs Division of the Pacific Missile Range conducted a computer simulation study employing a surveillance satellite to detect and report the positions of ships at sea. The purpose of the study was to determine, for a given satellite sensor capability and orbit, the times and positions of ships at sea eligible for detection by the satellite. The ship data used in the study was extracted from actual weather reports. (The studies are reported in detail in Pacific Missile Range Technical Note No. 3285-570, 1964.) The Pacific Missile Range program permitted the user to describe the orbit of a satellite in altitude and inclination to the earth's equator. It also permits the analyst to specify several different sensor capabilities. Ship's call signs, reported position, time, and cloud cover were extracted from the weather reports, and from this, tracks were projected. The simulation program then determined the times and positions of the ship at which the satellite would be in a position to detect the ship with each of the sensors described by the user. The simulation program also determined whether this conjunction of ship and satellite occurred during daylight or darkness. A Monte Carlo process based on reported cloud cover was used to determine whether the ship

was obscured by clouds at the time of conjunction.

The object of this thesis is to provide the next logical step in the analysis of a surveillance satellite system, i.e., to devise a correlation logic to determine to what extent the sets of conjunctions provided by the Pacific Missile Range simulation can be processed to form tracks which correspond with the actual track as determined from the ship's weather reports. It will then be possible to determine the coverage frequency required to provide an acceptable tracking reliability, hence the number of satellites required. The authors have therefore addressed themselves to the task of devising correlation logic to provide programs which will facilitate further study of the feasibility and cost of tracking ships at sea by use of data collected by surveillance satellites.

2. General Analysis

The formulation of track correlation logic which will facilitate testing the feasibility of satellite surveillance of ocean shipping, has been undertaken via two different approaches. The two procedures considered are described in detail in the following two chapters. In the development of both procedures it is assumed that the input data to the tracking program will consist only of the time of conjunction and the geographical position of the contact at the time of conjunction. Thus the analysis is not dependent upon the development of a high resolution sensor which might provide information about the ship's course by virtue of its orientation to the orbital path, or other identification clues, such as length or the number of stacks observed.

This study has been limited to a consideration of methods by which the data described above might be correlated in a computer program to derive tracks of ships at sea. No attempt has been made to determine optimal orbits or combinations thereof.

It is evident that ocean traffic intelligence gathered from other sources would be of significant value in decreasing the uncertainty involved in surveillance by satellites. Such other sources include sighting reports by aircraft and friendly shipping, reports of ship arrivals and departures gleaned from commercial sources or news media, and voluntary reporting of own position by ships at sea. If one half of the ships in a certain area can be identified by means of external intelligence, the number of possible correlations to be determined may be reduced to one quarter of what would otherwise be required. This report will not concern itself with the methodology or effect of such an input to the tracking program, for if tracking can be shown to be feasible using information gathered solely by the surveillance satellite,

it will clearly be enhanced by inclusion of externally gathered information.

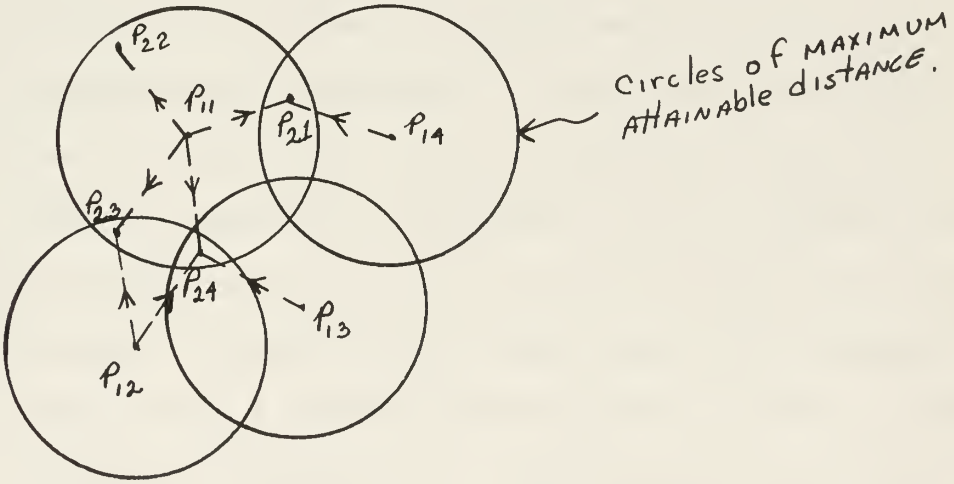
2.1 The Correlation Problem

The correlation problem can be thought of as consisting of two parts. The first and most difficult part involves track initiation, i.e., making a decision as to which pair of positions reported on consecutive orbits form the most probable true correlation. Once this decision has been made, the track can be considered as true and the course and speed of this designated track then becomes available for the second part of the problem, the track extension.

Track Initiation. The speed with which ships sail the surface of the oceans is less than some generally known maximum speed. Few ships today can sustain a speed in excess of 40 knots for more than a few hours. An analysis of merchant ship cruising speeds reveals that their distribution is approximately normal with a mean of 14.0 knots and a standard deviation of 2.5 knots. Only 2.0% of the cruising speeds exceeded 19 knots while 78.5% were in the range 11.5-19.0 knots. The inclusion of military ships in the analysis presumably would bias the results toward somewhat higher speeds but even fast naval ships seldom cruise at speeds in excess of 20 knots. Thus it may be reasoned that a correlation between two position reports which indicates a speed of 16 knots is much more likely to be a true correlation than one which indicates a speed of 10 knots or 25 knots. The existence of this speed limitation determines a selection rule for track initiation which permits the elimination of all possible correlations between position reports which would require a speed in excess of some specified maximum speed. In many cases this selection rule alone will determine the correlation. i.e., if for a point from one sweep there is only one

corresponding point from the next sweep which is within a circle whose radius is equal to the maximum speed attainable multiplied by the time between the position reports, then there is a high probability that these two points can be correlated as a true track. It is evident that any tracking program must not deny correlations showing very high or very low speeds, but much more confidence can be placed on a correlation which indicates a speed in the range of 12-18 knots.

The difficulty of correlation increases when a number of possible correlations occur within this maximum distance circle. The number of tracks to be considered as possible for position reports from two orbits is equal to the number of points from the second orbit which lie within the maximum distance circles drawn about the points from the first orbit. This situation is illustrated in Figure 1. In areas of high shipping density it is to be expected that the picture will be much more complicated than that illustrated.



Note: The notation p_{rn} refers to report number n on orbit number r.

Illustration of Possible Tracks for a Given Situation

Figure 1

When the circles of maximum attainable distance are drawn in accordance with the selection rule for track initiation it can be seen that while p_{11} may link with all four points obtained on orbit two, the same is not true for p_{12} , p_{13} , and p_{14} . Thus it can be assumed that since p_{14} can only correlate with p_{21} , then p_{21} cannot be logically considered as a possible correlation for p_{11} . A similar reasoning applies to p_{13} , and p_{24} . If p_{24} is removed from consideration with p_{12} , then p_{12} can be linked with p_{23} . The result of applying the selection rule on the position reports illustrated in Figure 1 therefore reduces the eight possible tracks illustrated to the following firm correlations:

p_{14} -- p_{21}
p_{13} -- p_{24}
p_{12} -- p_{23}
p_{11} -- p_{22}

This selection rule cannot stand alone however, since it is heavily dependent upon the assumption of a sensor which is 'perfect' in the sense of a radar with a blip-scan ratio of one, i.e., if a ship is within the sweep path of the sensor it will be detected by the sensor with probability one. It cannot be strictly applied when the circle of maximum attainable distance drawn about a point encloses a seaport since there is a possibility that the ship did enter port and was not detectable by the satellite. Similarly, any ship detected within a circle of maximum attainable distance drawn about a seaport may be a ship just starting her voyage from that port. The rule also ignores the possibility of a temporarily surfaced submarine or occasional data points resulting from contacts with aircraft or heavy clouds.

Track Extension. After tracks have been initiated, a rule of consistency utilizing both course and speed can be applied to determine the extension of tracks for position reports from consecutive orbits. This rule is one that states the extension of initiated tracks to new position reports can be done on the basis of course and speed consistency. Ships at sea are generally steaming from one port to another port and have selected a direct course. This implies that most course changes in general are executed to circumnavigate points of land or are occasioned by circumstances such as avoidance of severe weather, mid-course changes in destination, or navigational course adjustments necessitated by the effects of wind and sea. Ship cruising speeds are also usually constant and are determined by economical considerations, with slight variations to permit favorable entry conditions at the destination.

There are exceptions to this rule of consistency. Fishing vessels off the Grand Banks follow very erratic maneuvering patterns. Navy ships executing training maneuvers or on certain patrol missions do not follow consistent course patterns. Since these exceptions apply to only a small fraction of world ocean traffic, a sequence of data points, i.e., position reports, which indicates a consistent course and speed is probably an actual ship's track.

There are certain geographical areas where the antithesis of consistency is true. For example, ships approaching the Straits of Malacca from the north-east will, with a very high degree of certainty, change course radically to the north-west at the mouth of the strait. A highly sophisticated correlation program will be cognizant of the conditions and locations where these exceptions occur. However, even lacking this sophistication, much of the confusion resulting from circumnavigation

course changes will be resolvable by lending more credence to speed consistency than to course consistency in these areas.

2.2 Application

Each of the selection rules discussed have certain application limitations. One must conclude that an optimal correlation procedure would use them both to a certain degree, or in certain cases, but be able to distinguish when the selection rules break down. It is also the case that the longer the sequence of positions to be considered by the correlation logic, i.e., the smaller the interval between orbits, the more confidence one may place in the results. Certainly, there can be no less than a sequence of three points for consideration in order to initiate and extend tracks.

The two correlation programs considered by the authors are described in detail in the next two sections. These programs employ both of the selection rules to some extent, but each emphasizes a different aspect. The first program, the deterministic correlation model, examines several sets of position reports at one time and makes maximum use of the selection rule for initiating tracks, i.e., the elimination of consideration for correlation of two position reports from consecutive orbits which are separated by a distance greater than the distance attainable by a ship cruising at the arbitrarily stated maximum speed throughout the period between orbits. The second program, the probabilistic correlation model, emphasizes the selection rule for track extension, i.e., the greater reliance on consistent course and speed to select the most probable correlation. After considering each new data set, this program presents a list of all possible tracks together with a credibility factor which reflects the consistency of course and speed indicated by each.

The probabilistic model will be described in detail in section four.

Section three contains a discussion of the logic, step-by-step procedure for correlation, and details the methods and results of the simulation used to evaluate the deterministic correlation model.

3. The Deterministic Correlation Model

The deterministic model attempts to correlate reports of the position of ships at sea as obtained and relayed by surveillance satellites. Explicit use of probability theory is avoided. No reference is made to information such as normal cruising speed, or the existence of the more or less well defined shipping lanes between seaports. Externally gathered intelligence information concerning shipping is not used by this model in its present level of development. The model is designed to permit track initiation and track extension by accumulating position reports from several orbits and correlating them concurrently. As it now stands, this model is a mid-ocean model. It has no logic for correlating position reports in proximity of seaports.

To facilitate formulation of this model, certain assumptions have been made about the capabilities and characteristics of surveillance satellites and ocean shipping.

These assumptions are:

1) On every orbit the satellite borne sensor will report the position of all ships on the ocean that are within its range of detection.

2) All positions reported will be positions of ocean shipping. Clouds, aircraft, land and objects on or over land will not be reported.

3) Two positions reported at times differing by dt cannot correlate if they are separated by a distance greater than the product of dt and S_{mx} , where S_{mx} is an arbitrarily stated maximum speed attainable by ocean shipping.

4) A ship reported on orbit i will also be reported on orbit i + 1. That is, the ship cannot enter port and thus avoid detection. This disregards the possibility of submarines being detected on orbit i and submerging before orbit i + 1.

3.1 The Correlation Logic

Let $P_{i,n}$ be the set of n positions, $p_{i,1}, p_{i,2}, \cdots, p_{i,n}$ reported on orbit i. Let $Q_{i,j}$ be the set containing all of the positions of set $P_{i+1,m}$, which are within a distance d of $p_{i,j}$, where d is the maximum distance a ship can travel in the time between orbits i and i + 1 at speed S_{mx}, and $p_{i,j}$ is an element of $P_{i,n}$. Define n_q as the number of elements in the set $Q_{i,j}$. Then

$$P_{i,n} = \left\{p_{i,1}, p_{i,2}, \cdots, p_{i,j}, \cdots, p_{i,n}\right\}$$
$$Q_{i,j} = \left\{p_{i+1,k} \mid p_{i+1,k} \in P_{i+1,m} \text{ and is within distance d of } p_{i,j}\right\}$$

The number of elements in $Q_{i,j}$ is greater than or equal to one, i.e., $1 \leq n_q \leq m$, since under the assumptions stated above, all ships reported at orbit i will also be reported at orbit i + 1 and none will have travelled a distance greater than d, the maximum attainable distance at speed S_{mx}.

The step-by-step procedure for the concurrent correlation of ship position reports in the deterministic model is:

1) Construct the sets $Q_{i,j}$ for all $p_{i,j}$.

2) Determine which, if any, of the $Q_{i,j}$ have only one element.

3) If any position which is the only element of a one element set is also included in any other set $Q_{i,j}$, remove it from those other sets.

4) Repeat steps 2 and 3 until no more changes can be made.

5) For each $Q_{i,j}$ containing only one element a firm correlation exists between a position of orbit i and a position from orbit i + 1. Confirmation of this correlation is sought by projecting the track to the next (or prior) orbit. If the track is confirmed by the presence of a ship in the area of the projected position, the correlation is designated as a track.

6) Attempt to trace each designated track from the time of its designation back to orbit one and forward to the last orbit reported.

7) Attempt to correlate tracks for the sets $Q_{i,j}$ containing more than one element.

8) Attempt to correlate all remaining uncorrelated position reports.

Step 6 above is accomplished by the following methodology:

a) Using the course and speed indicated for the designated track, determine the next projected ship position by projecting the track ahead (or back) to the time of the next (or previous) orbit.

b) Define an area about this projected position and determine whether an undesignated position report from the next (or previous) orbit is located within this area. The size of the area defined can be varied as a function of the expected inaccuracies of reported positions.

c) If only one ship position report is in the defined area, and if that position report is not simultaneously in the area defined about another projected position, it is assigned as an extension of the designated track. This position report is then removed from all other sets, $Q_{i,j}$, which may contain it.

d) Repeat (a) through (c) until each designated track is extended as far as possible.

e) Return to Step 2 until no further designations can be made on the basis of the deletion of elements from the sets $Q_{i,j}$.

If more than one ship position report, or if no ship position report, is in the defined area, the projected track cannot be extended by the methodology for Step 6.

At the completion of Step 6, the methodology for Step 7 is:

a) For each $Q_{i,j}$ consider the relation between $p_{i,j}$ and

each element of $Q_{i,j}$ as a tentative track.

b) Determine the projected positions for each of these tracks by projecting each tentative track to the next (or previous) orbit.

c) Define areas about each of these projected positions. If only one of the areas contains a position report, this position report is considered as defining a designated track.

d) For all tracks so designated, return to Step 6.

Those $Q_{i,j}$ which still contain more than one element, as a result of the areas constructed about the projected positions containing other than one ship, are analyzed to determine which ship is closest to the projected position. That position report which is closest is considered to be the most likely correlation and is designated. The track is then extended as in Step 6.

In summation, the correlation logic for the deterministic model is based upon the previously stated assumptions and upon the following concepts:

1) Any set $Q_{i,j}$ which contains only one element determines a unique correlation with certainty of being correct.

2) Tracks which are tentatively extended to a constructed area which is occupied by more than one ship, can be correlated on the implicit probability that the ship nearest to the center of the area is the most likely true correlation.

3) Any track projecting to an area which contains no position reports does so as the result of a ship course or speed change. Based upon the implicit probability that a small course change or a small speed change is more probable than a larger course or speed change, the undesignated position report nearest to the center of the constructed area is considered

to be the most likely true correlation.

Although some of the correlated positions may have been correlated erroneously due to changes in the course or speed of the ships, the assumption that each ship is reported on each orbit assures that eventually all positions will be correlated.

3.2 Applications of the Model

A simple situation illustrating one of the basic principles of this logic is diagrammed in Figure 2.

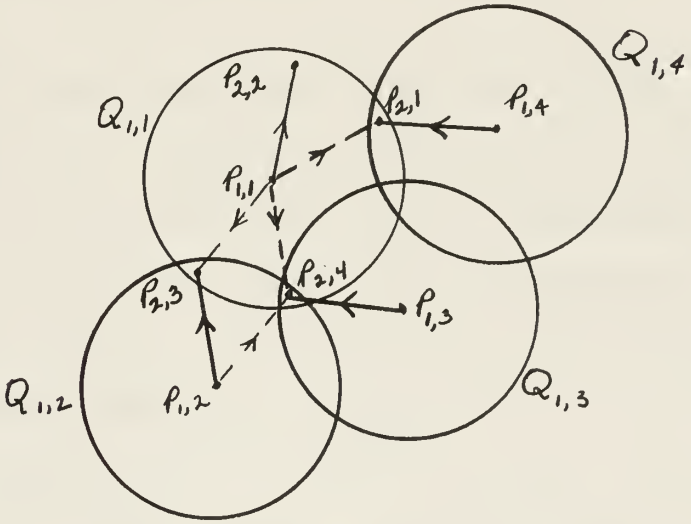


Illustration of One of the Basic Principles of the Deterministic Correlation Model Logic

Figure 2

Four position reports from orbit one and four position reports from orbit two are plotted and the $Q_{i,j}$ have been constructed about each $P_{i,j}$. The true tracks are drawn in solid lines with other possible tracks indicated by dashed lines. The position report $p_{1,j}$ can

be correlated only with members of the associated $Q_{1,j}$. To permit other correlations would violate the assumption concerning the maximum speed attainable. Due to the assumption that the position of each ship reported at orbit one will also be reported at orbit two, we are assured that each of the eight position reports plotted can be correlated. Therefore, the next step to be taken after the sets $Q_{i,j}$ have been constructed, is to determine which, if any, of the $Q_{i,j}$ have only one element. From Figure 2 it can be observed that $Q_{1,3}$ and $Q_{1,4}$ have only one element. This determines a correlation between $p_{1,3}$ and $p_{2,4}$ and a correlation between $p_{1,4}$ and $p_{2,1}$.

It is clear that a specific ship cannot occupy more than one position at a given time. Therefore $p_{2,1}$ and $p_{2,4}$ can be removed from set $Q_{1,1}$, and $p_{2,4}$ can be removed from set $Q_{1,2}$. Further examination now shows that $Q_{1,2}$ has only one element and a correlation can be established between $p_{1,2}$ and $p_{2,3}$. After deleting $p_{2,3}$ from set $Q_{1,1}$, a correlation is determined between $p_{1,1}$ and $p_{2,2}$.

Although $p_{1,1}$ had four tentative tracks, a unique correlation of $P_{1,4}$ and $P_{2,4}$ has been made. This simple, easily resolvable situation is not likely to be encountered frequently, but it does serve as a basis and as a first step toward resolving more complicated situations.

Figure 3 illustrates a situation requiring the application of all of the steps outlined in section 3.1 above. Four position reports from each of four orbits are plotted. Actual tracks are indicated by solid lines while tentative tracks and projections thereof are indicated by dashed lines. The circles indicate the areas constructed around projected positions. The circles defining the sets $Q_{i,j}$ are omitted for the sake of clarity.

The $Q_{1,j}$ are constituted as follows:

$$Q_{1,1} = p_{2,1} , p_{2,2} , p_{2,4}$$
$$Q_{1,2} = p_{2,1} , p_{2,2} , p_{2,4}$$
$$Q_{1,3} = p_{2,1} , p_{2,3} , p_{2,4}$$
$$Q_{1,4} = p_{2,1} , p_{2,2} , p_{2,4}$$

The tentative tracks contained within $Q_{1,3}$ have been omitted from the figure for clarity.

Since none of the $Q_{1,j}$ contain single elements, the tracks are initiated by projecting each of the tentative tracks and checking for position reports in the constructed areas. In this case only one of the tentative tracks projected from each of the $p_{1,j}$ results in an occupied area. Therefore all four tracks are initiated correctly. When track one and track three are projected from orbit three to orbit four, a conflict situation occurs. Both projections find an area occupied by two ships. This situation is resolved by comparing the distances of the tentative projections from the center of the area projected by the course and speed of the designated tracks, i.e., track one is projected to orbit four and finds $p_{4,1}$ and $p_{4,3}$ both in the area. However, $p_{4,1}$ is nearest to the center of the area and is the favored correlation.

Tracks two and four, when projected from orbit three to orbit four, find only one ship in their respective projected areas, but it is the same ship, $p_{4,2}$. A comparison of the distance from $p_{4,2}$ to the center of each of the projected areas shows track two to be favored and leaves track four with an empty area. The program must then look to the other members of $Q_{3,4}$. Since, due to the deletion of elements from $Q_{3,4}$ as they were assigned designations by other tracks, $p_{4,4}$ is the only remaining element in $Q_{3,4}$ it is correlated with track four.

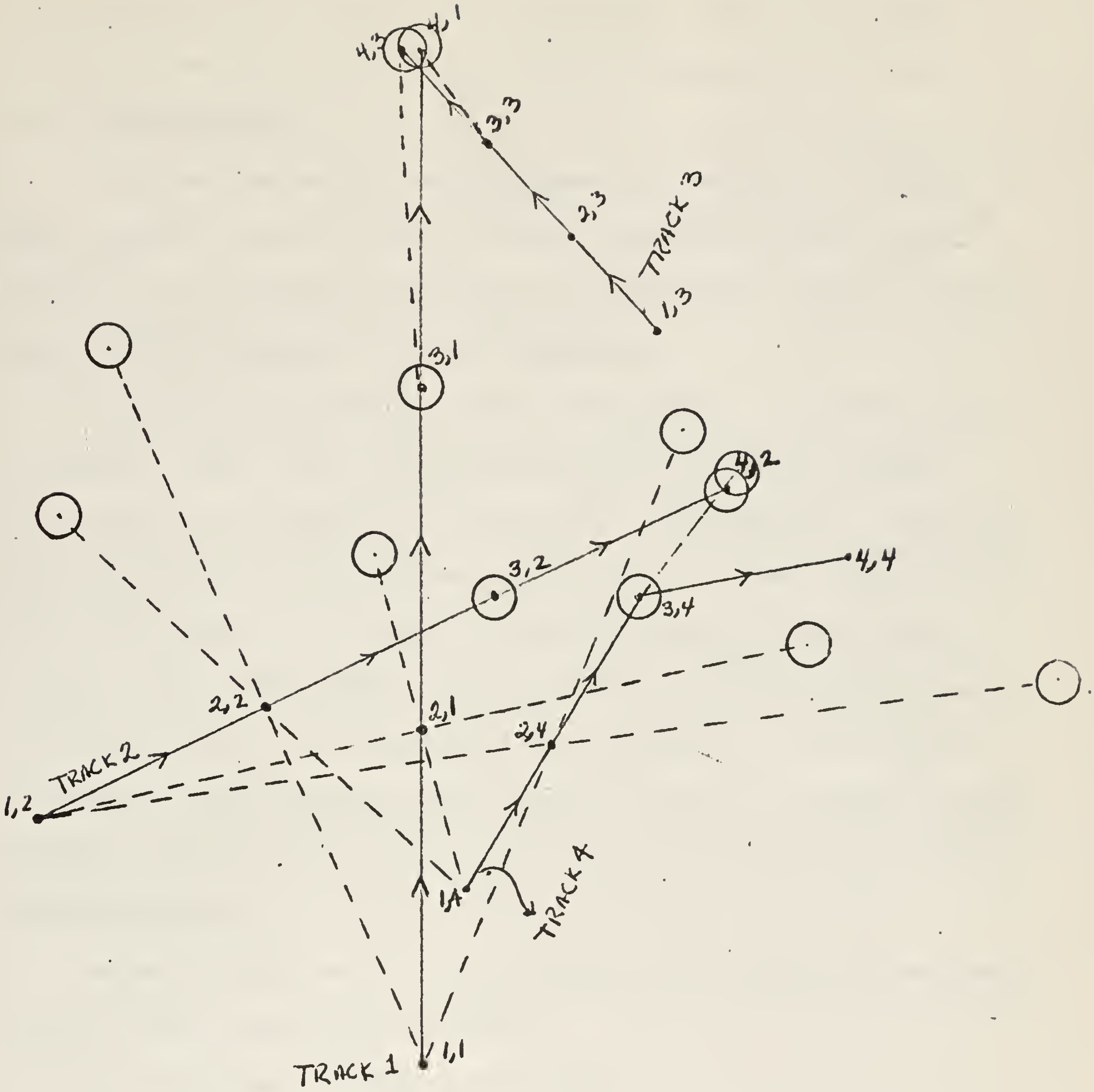


Diagram of Track Initiation and Extension

Figure 3

These two illustrations by no means point out all of the complications that may arise in track correlation. They are intended merely to demonstrate some of the fundamental points of the logic.

3.3 Model Evaluation

This correlation model was programmed for evaluation on the CDC 1604 computer located at the U.S. Naval Postgraduate School computer facility. The program was written in the FORTRAN 63 computer language. The FORTRAN 63 program is listed in Appendix I.

The program was designed to have the capability to receive a wide variety of inputs. Data representing specially designed shipping situations can be entered into the program. Alternatively, situations can be generated by the computer program by use of random number generators. The program is written to correlate positions gathered from several orbits concurrently with none of the tracks designated prior to the initial orbit. It is considered that ability to resolve such a situation is more demanding than a situation where the program is merely asked to extend tracks previously designated and correlate them with new position reports.

Parameters that can be varied to permit full analysis of the correlation program capabilities include:

1) The number of ships to be tracked.

2) The number of orbits to be processed concurrently.

3) The time between orbits. For correlation of positions in a concentrated area, the speed of the satellite passage is so large relative to the speed of the ships being tracked and the area concerned, that it does not invalidate the evaluation to consider that all of the positions reported during one orbit over the target area have been taken simultaneously.

4) The size of the area containing the initial positions of all ships. This parameter determines the shipping density.

5) The distribution of initial courses.

6) The distribution of initial speeds.

7) The distribution of initial positions within the playing area.

8) The distribution of the number of course and speed changes to be made.

9) The distribution of the magnitudes of course and speed changes to be made.

10) The size of the areas to be constructed about the projected positions. If it is required that the area size be incremented to look for ships that have changed course or speed, the program specifies that both dimensions of the area will be doubled.

Provisions are also included that permit bypassing the routine which looks for the sets $Q_{i,j}$ which have only one element. When this provision is bypassed, the tracks are initiated by projecting all tentative tracks ahead to the next orbit and checking for area occupancy. Decisions are then made on the basis of minimizing the distance between the center of projected areas and the correlated positions.

The first evaluation of the model involved the correlation of ten position reports received per orbit for five orbits. The time between orbits was chosen as one hour. The initial positions of the ten ships were uniformly distributed in a 200 mile square. Initial speeds were uniformly distributed in the interval 5-35 knots. Initial courses were uniformly distributed on the interval 0-360 degrees subject to the constraint that no ship was assigned a course which would prohibit that ship from being included in the $Q_{i,j}$ associated with a position of some other ship. No course or speed changes were made.

This situation was correlated once using the entire logic and once omitting the check for $Q_{i,j}$ which contain only one element. All positions were correctly correlated, designated and tracked for all orbits. There was no detectable difference between the evaluation with and without the check for single element $Q_{i,j}$.

The above situation was modified by changing the area containing the initial positions from a 200 mile square to a 100 mile square, and the evaluation was repeated with identical results.

Using the same initial positions, initial courses and speeds, and the same area, the situation was modified to provide large course and speed changes at the time of orbit three for three ships. Additionally, one ship was provided with a new course and a new speed on every orbit. The model was again successful in correctly correlating, designating, and tracking all ships thru all orbits.

The model was next evaluated using randomly generated data under the following constraints:

1) Ten ships were to be tracked.

2) Five orbits were to be processed concurrently.

3) The initial positions of all ships was uniformly distributed in an area by use of a random number generator. The size of the area was varied as a parameter.

4) Initial courses were generated from a uniform distribution on the interval 0-360 degrees.

5) Initial speeds were generated from a normal distribution with a mean of 15 knots and a standard deviation of 5 knots, subject to the constraint that the minimum speed was 5 knots and the maximum speed was 35 knots.

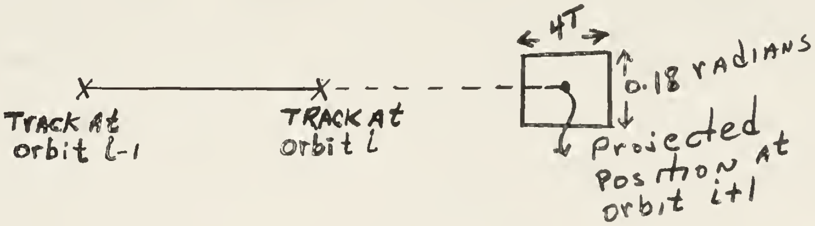
6) For each of the last three time intervals the number of ships to change course and the number of ships to change speed were generated from a uniform distribution on the interval 2-8.

7) The determination of which ship was to make each change was made by generation of a random integer on the interval 1-10.

8) The magnitude of the course change was generated from a normal distribution with mean zero and with a standard deviation of 0.50 radians.

9) The magnitude of the speed change was generated from a normal distribution with mean zero and with a standard deviation of five knots subject to the constraint that the resulting speed must lie on the interval 5-35 knots.

10) Given a designated or tentative track at orbit i, the initial area to be searched for the extension of this track is centered on its projection from orbit i to orbit i + 1. The area extends ± 2T miles radially and ± 0.09 radians in azimuth, where T is the time interval between orbit i and orbit i + 1. The radial dimension of the area is a function of T, while the angular dimension is a function of the distance from the area center to the track position at orbit i, i.e., a function of track speed and T. Figure 4 illustrates this area definition:



Definition of Area Constructed Around Projected Positions

Figure 4

It is to be noted that the number of course and speed changes permitted for this test significantly exceed the number to be expected under any but the most peculiar situations to be encountered at sea. Further, the standard deviation stated for the magnitude of course and speed changes is considerably larger than that which would be expected under normal conditions at sea. These larger values are specified for this evaluation to provide a more severe test of the capabilities of this model.

Figure 5 summarizes the test simulations, the simulation results, and indicates the parameters which were varied. A sample simulation and the results of the correlation are contained in Appendix II. While the availability of computer time prohibited conducting sufficient simulations to permit a rigorous statistical analysis of simulation results, the number of simulations conducted did indicate some general relationships between the various parameters and the results. A comparison of columns five and six of Figure 5 indicates that a major portion of the incorrect track extensions involved the extension to the position reports obtained on orbit one. This is attributable to the much greater shipping congestion at that time due to the initial positioning constraints. A major drop in program performance is indicated for the evaluations with an orbit interval of 8.0 hours and an initial area of 50 miles square or of 100 miles square. This drop is explained by noting that for each of the 80 simulations conducted under these conditions, each of the $Q_{1,j}$ constructed about the position reports from orbit one contained all of the positions reported on orbit two. A modification to preclude any course or speed change until three orbits had been completed was made for 20 simulations at 8.0 hour orbit intervals.

This required all ships to maintain a steady course and speed for 16 hours. Under these conditions the effectiveness increased from 49% to 72% as indicated in Figure 5. In all of the simulated situations, many of the ships that were not correctly tracked through all orbits, were correctly tracked through four orbits.

Column 1 SIZE OF SQ. CONTAINING INITIAL POSITIONS OF ALL SHIPS	Column 2 AVERAGE NO. OF COURSE AND SPEED CHANGES PER SIMULATION	Column 3 NUMBER OF SIMULATIONS	Column 4 ORBIT INTERVAL (HOURS)	Column 5 PERCENTAGE OF SHIPS CORRECTLY TRACKED THRU ALL ORBITS	Column 6 PERCENTAGE OF SHIPS CORRECTLY TRACKED THRU LAST FOUR ORBITS
100.0	26.9	42	1.0	94.0	96.2
50.0	21.8	44	1.0	82.0	90.5
50.0	16.3	22	2.0	85.4	93.7
50.0	23.8	40	8.0	28.3	86.5
100.0	23.0	40	8.0	49.0	90.7
*100.0	22.5	20	8.0	72.0	93.5
500.0	29.8	20	8.0	81.5	90.5

* For these simulations, all course and speed changes were made for the last two orbits.

Summary of Test Simulations for Deterministic Model

Figure 5

3.4 Conclusions

The following conclusions are permitted by the results of the model evaluations discussed in section 3.3 above:

1) Under the stated assumptions, ships that maintain a steady course and speed will be correctly correlated, designated, and tracked in almost every case.

2) For a shipping density of 10 ships per 50 mile square or less and for an orbit interval of 2 hours or less, the model performs track correlation with a high degree of reliability and precision, even when a large number of course and speed changes are permitted.

3) For an orbit interval of 8.0 hours the model correlates tracks with a high degree of reliability and precision after the ships have departed from the congested area imposed by the initial problem conditions.

4. The Probabilistic Model

The probabilistic model attempts to correlate all position reports obtained from the latest sweep of an area with all previously uncorrelated position reports and all previously established tracks in order to determine all possible track extensions. A track reliability factor is then assigned to each extension to express the probability that this extension is the correct one. In this model track extension is primarily a function of the selection rule of velocity consistency as discussed in Section 2 while the track reliability factor includes those factors which must be considered in making a probability determination. What these factors are and how they enter the computation of the reliability factor form the logic of the probabilistic model. In the discussion to follow, the notation developed in Section 3 will also apply, i.e., $P_{i,n}$ is the set of all position reports, $p_{i,1}, p_{i,2}, \ldots, p_{i,n}$ reported from the i^{th} sweep.

In order to determine the reliability factor used in this model the possible results of correlating any one position report into a track extension are examined. For any point $p_{i,j}$ from the set $P_{i,n}$ and a current track A, the set of all possible events in extending track A to the set $P_{i,n}$ is:

E_1: $p_{i,j}$ is the true extension of track A, or

$\bar{E}_1$: $p_{i,j}$ is not the true extension of track A.

The probability of the event E_1 occurring, $P(E_1)$, is

$$P(E_1) = 1 - P(\bar{E}_1)$$

Upon further examination the event $\bar{E}_1$ can be seen to include the following mutually exclusive events:

E_2: $p_{i,j}$ is the true extension of some other track X, while some other point $p_{i,k}$ is the true extension of track A.

E_3: $p_{i,j}$ is the true extension of some other track X and track A has terminated since last sweep.

E_4: $p_{i,j}$ represents a ship which has put to sea since the last sweep, with no previous track, and some other point $p_{i,k}$ is the true extension of track A.

E_5: $p_{i,j}$ has no previous track and track A has terminated.

The probability of $\bar{E}_1$ occurring is therefore

$$P(\bar{E}_1) = P(E_2) + P(E_3) + P(E_4) + P(E_5)$$

and

$$P(E_1) = 1 - (P(E_2) + P(E_3) + P(E_4) + P(E_5)) \tag{4-1}$$

It should be noted that inherent in equation (4-1) is the assumption that all ships are detected and their positions reported on each sweep by the surveillance satellite.

The value of $P(E_1)$ obtained in equation (4-1) should be the value of the reliability factor used in this model. However, none of the probabilities in the right side of equation (4-1) can be computed directly. The value of $P(E_1)$ can at best be estimated. In the sub-sections to follow, equation (4-1) serves as a guide for obtaining a best estimate of $P(E_1)$.

4.1 Probability Based on Velocity Consistency

This section sets forth the methodology for determining a probability of correlation based on the selection rule of constant course and speed. Basic to this methodology is the assumption that course change and speed change are independent events. This assumption is based on the observations made in section 2.1 concerning circumstances governing course and speed changes.

If the probability density function for speed change is continuous the probability that a ship will change speed exactly k knots is zero, regardless of the value of k. In order to obtain a positive probability, a small margin of error, Δx, must be introduced. If $f_s(x)$ is the probability density function for speed change, the probability that a ship will change speed by an amount $k \pm \Delta x$ is:

$$\int_{k-\Delta x}^{k+\Delta x} f_s(x)dx$$

However, this computation will still yield a very small probability even when the speed change, k, is zero, the most likely value. In order to determine a more meaningful value, therefore, the probability of a correlation p_s, showing a speed change of $k \pm \Delta x$ as compared to the probability of a correlation which shows the most likely speed change, $0 \pm \Delta x$, is used.

This probability of correlation is computed as the ratio of these probabilities, i.e.,

$$p_s = \frac{\int_{k-\Delta x}^{k+\Delta x} f_s(x)dx}{\int_{-\Delta x}^{+\Delta x} f_s(x)dx}$$

However, for constant Δx in both numerator and denominator, this ratio can be assumed to be:

$$p_s = \frac{f_s(k)}{f_s(0)} \qquad (4.2)$$

The probability of the correlation based on course change p_θ, is developed in precisely the same way and if $f_\theta(x)$ is the probability density function for course change then

$$p_\theta = \frac{f_\theta(k)}{f_\theta(0)} \qquad (4.3)$$

where k is some representative value of course change.

The probabilities, p_s and p_θ, represent two independent estimates of the probability for a valid track between position reports as a function of consistent velocity. A best estimate of this probability is some linear combination of the two. In this model it is assumed that this best estimate for a given course and speed change is $p_{s\theta}$, where

$$p_{s\theta} = \frac{p_s + p_\theta}{2}$$

The development of $p_{s\theta}$ thus far applies only for those tracks that previously existed in the model for which a course and speed were known. New tracks may be initiated in the model by connecting position reports from the previous sweep of the area which cannot be correlated with new position reports from the current sweep. In such a case there is no track history from which to determine a value of course and speed change. The discussion in section 2.1 implies that a truncated normal probability density function exists for ships' cruising speeds. For a correlation between a new position report and a previously uncorrelated report, the probability, p_c, is used in this model instead of $p_{s\theta}$, where

$$p_c = \frac{f_c\ (k)}{f_c\ (\mu_c)}$$

and $f_c(x)$ is assumed to be the truncated normal distribution with $\mu_c = 14$ knots and $\sigma_c = 2.5$ knots and where k is the speed indicated by the time and distance between the position reports. This is to say that in the track extension phase, i.e., the phase for extending established tracks, $p_{s\theta}$ is assigned to all possible extensions in an effort to determine the most likely, while in the track initiation phase, p_c is assigned to all possible correlations between new position reports and previously uncorrelated positions.

For the evaluation of this model the density functions, $f_s(x)$ and $f_\theta\ (x)$, were assumed to be truncated normal with the parameter values $\mu_s = 0$, $\sigma_s = 2.5$ for s in knots and $\mu_\theta = 0$, $\sigma_\theta = 24$ for θ in degrees. No statistical justification is offered for the use of these distributions. They were selected because they seemed to be reasonable in the experience

of the authors. The methodology, however, would be the same regardless of the distributions used. It may be that experimentation or thorough statistical analysis will yield distributions which provide more accurate likelihood. These distributions, however, appear to adequately represent the conditions of velocity consistency for ocean going ships.

Using these truncated normal distributions the desired probabilities are:

$$p_s = \frac{\frac{1}{t\sigma_s\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{K}{\sigma_s}\right)^2}}{\frac{1}{t\sigma_s\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{0}{\sigma_s}\right)^2}} = e^{-\frac{1}{2}\left(\frac{K}{\sigma_s}\right)^2} \qquad (4.2)$$

and in a similar fashion

$$p_\theta = e^{-\frac{1}{2}\left(\frac{\theta}{\sigma_\theta}\right)^2} \qquad (4.3)$$

$$p_c = e^{-\frac{1}{2}\left(\frac{\ell-\mu_c}{\sigma_c}\right)^2} \qquad (4.4)$$

where θ = the amount of course change.

k = the amount of speed change.

ℓ = the speed indicated between position reports.

and

t = the truncation factor.

4.1.1 Probability Based on Mutually Exclusive Events

The factor $p_{s\theta}$ expresses a likelihood that a particular track extension is a valid one based on the consistency of course and speed. In the probability sense, the set of all $p_{s\theta}$ for the extension of some track A cannot be considered as a mass function to determine which extension of A has the highest probability of being valid. This is the

case because, in general, the set of all $p_{s\theta}$ for track A will not sum to unity. However this situation may be overcome by assuming that all possible extensions of track A from $P_{i,n}$ to $P_{i+1,n}$ and the associated $p_{s\theta}$ form a set of mutually exclusive, exhaustive events. Thus a likelihood factor that represents the probability of a track extension being valid in view of the k possible extensions can be computed as

$$L(Ap_{i+1,j}) = \frac{(p_{s\theta})_j}{\sum_{i=1}^{k} (P_{s\theta})_i}$$

where

$L(Ap_{i+1,j})$	is the probability of $p_{i+1,j}$ being the valid extension of track A with respect to consistent velocity and all other possible extensions of track A.
$(p_{s\theta})$	is computed as in section 4.1.
k	is the total number of possible extensions of track A.

It should be noted that the relative magnitude of the $p_{s\theta}$ have been preserved in the construction of $L(Ap_{i+1,j})$. For example: if $k = 1$, $L(Ap_{i+1,j}) = 1.0$ and if $k = 3$ and these three possible track extensions are equally likely then $L(Ap_{i+1,j}) = .333$ for all three regardless of the value of $p_{s\theta}$.

This same development applies to the computation of the probability of a newly initiated track being a valid one based on the speed indicated and weighted by the number of other possible new position reports which could be correlated with the previously uncorrelated position. The only difference is the use of p_c instead of $p_{s\theta}$ wherever the latter appears.

4.1.2 Probability Based on Cross Mutual Exclusion

The factor $L(Ap_{i+1,j})$ is developed by a consideration of all position reports $p_{i+1,j}$ from the set $P_{i+1,m}$ which fall within the distance S_{mx} of the last known position of track A. It is also possible that the position report $p_{i+1,j}$ is considered as a possible extension of more than one track, say tracks A, B, and C. If this is the case then there is an associated $p_{s\theta}$ as computed in section 4.1 for each of these possible tracks. The arguments presented in section 4.2 for the development of $L(Ap_{i+1,j})$ will again hold and a new probability factor $L(p_{i+1,j}A)$ can be defined which reflects the velocity consistency of $p_{i+1,j}$ with respect to track A normalized over the other tracks for which $p_{i+1,j}$ could be the extension, i.e.,

$$L(p_{i+1,j}A) = \frac{(p_{s\theta})_j}{\sum_{i=1}^{\ell} (p_{s\theta})_i}$$

where

$L(p_{i+1,j}A)$ is the probability of $p_{i+1,j}$ being the valid extension of track A based on consistent velocity and all other possible tracks for which $p_{i+1,j}$ could be the valid extension.

$p_{s\theta}$ is computed as in section 4.1, and

ℓ is the total number of track extensions containing $p_{i+1,j}$.

At this point the difference between $L(Ap_{i+1,j})$ and $L(p_{i+1,j}A)$ should be noted. $L(Ap_{i+1,j})$ is the probability that position report $p_{i+1,j}$ is the valid extension of track A with respect to all other

position reports that may be valid extensions of track A. $L(p_{i+1,j}A)$ however is the probability that position report $p_{i+1,j}$ is the valid extension of track A with respect to all other tracks that may contain $p_{i+1,j}$.

The following computations can now be made:

$\overline{L(Ap_{i+1,j})}$ $\equiv$ the probability that some position report, say $p_{i+1,k}$, other than position report $p_{i+1,j}$ is the valid extension of track A.

$= 1 - L(Ap_{i+1,j})$,

and

$\overline{L(p_{i+1,j}A)}$ $\equiv$ the probability that position report $p_{i+1,j}$ is the real extension of some track other than track A

$= 1 - L(p_{i+1,j}A)$.

Referring to equation (4-1), $P(E_2)$ can be computed as:

$$P(E_2) = \overline{L(Ap_{i+1,j})} \times \overline{L(p_{i+1,j}A)}$$

4.2 The Probability of Track Termination and Initiation

Neglecting the last three terms of equation (4-1), a good estimate of $P(E_1)$ based on velocity consistency and mutual exclusion with respect to both track A and $p_{i+1,j}$ is given by

$$P(E_1) = 1 - P(E_2)$$

This approximation of $P(E_1)$ does not include the possibility that track A has terminated or the possibility that $p_{i+1,j}$ represents a ship which

has just put to sea. Therefore, the possibility that tracks may be initiated or terminated between sweeps must be admitted for every track at each track extension phase.

Probability of track initiation. If λ is the mean rate of leaving port for ships all over the world then $1/\lambda$ is the mean interval between ships leaving port anywhere in the world. The average number of ships leaving port in a time interval t is therefore t/λ. If N is the average number of ships at sea the probability that any particular one of them left port in the time interval t is given by

$$L(-p_{i+1,j}) = \frac{t/\lambda}{N} = \frac{t}{N\lambda}$$

where, if t is the time interval between sweeps, then $L(-p_{i+1,j})$ is the probability that the ship represented by the position report $p_{i+1,j}$ put to sea between sweeps i and i+1. The justification for computing $L(-p_{i+1,j})$ in the manner shown above is the observation that ships put to sea in completely random fashion. This assumption is false at any particular port because the rate of departure depends on conditions of weather, tide, and daylight or darkness. However, over the world as a whole the effect of these factors at one port is assumed to be cancelled by opposite conditions at another. There are not an infinite number of ships as would be implied by a completely random distribution; however, there is a relatively large number of ships in existence compared to the number of ships at sea, and the turn around time as compared to voyage duration is relatively short. The effect is similar to an infinite supply of customers in a queue.

In the evaluation of this model the parameter values of λ and N

were chosen as .10 and 5000 respectively.

Probability of track termination. In order to determine the probability of a track terminating between sweeps the authors assumed a truncated normal distribution to represent the distribution of voyage lengths of ships at sea. Using this distribution the probability that a track will terminate between sweeps i and i+1, L(-A) can be computed as

$$L(-A) = \int_0^d \frac{1}{\sigma_t\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu_t}{\sigma_t}\right)^2} dx$$

where d is the total distance for track A from the point of initiation up to its position on sweep i+1.

There may be some justification in claiming that the probability of termination should be conditioned on the fact that the track was extended on a previous sweep, i.e., that the probability should be the probability that track A has terminated before sweep i+1 given that the track A had not terminated before sweep i. This conditional probability was not used in this model because the premise that the track had not terminated before sweep i is not a known fact. In the framework of the probabilistic model the track's existence on the last sweep is only a probability.

Based purely on the experience of the authors, the parameter values of mean voyage length μ_t = 3000 nautical miles and σ_t = 1000 nautical miles were chosen to test this model. More accurate parameters could be derived from a careful analysis of shipping records.

It should be noted that if this model were to be expanded to include a computation of the distance of a position from known sea ports then

both $L(-A)$ and $L(-p_{i+1,j})$ would be zero if the distance from port were found to be greater than S_{mx}.

The values of $P(E_3)$, $P(E_4)$, and $P(E_5)$ in equation (4-1) can now be found by using the values of $L(-A)$ and $L(-p_{i+1,j})$, i.e.,

$$P(E_3) = \overline{L(p_{i+1,j}A)} \times L(-A)$$

$$P(E_4) = \overline{L(Ap_{i+1,j})} \times L(-p_{i+1,j})$$

$$P(E_5) = L(-p_{i+1,j}) \times L(-A)$$

4.3 The Track Reliability

Utilizing the individual probabilities calculated in the preceding sub-sections, the complete formula used in estimating the probability that a particular correlation is a valid one, $P(E_1)$, is

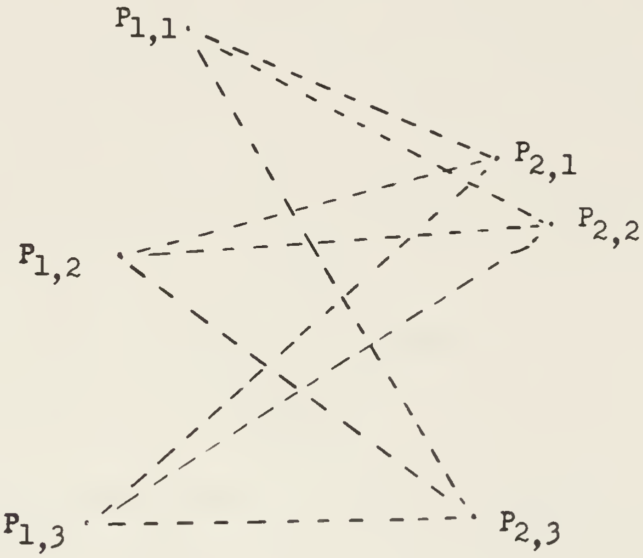
$$P(E_1) = 1 - \Big(\overline{L(Ap_{i+1,j})} \times \overline{L(p_{i+1,j}A)} + \overline{L(p_{i+1,j}A)} \times L(-A) + \overline{L(Ap_{i+1,j})} \times L(-p_{i+1,j}) + L(-p_{i+1,j}) \times L(-A) \Big)$$

This estimate is the track reliability factor used in this model to determine both the most likely new tracks and the most likely extensions for established tracks. In the next section a detailed sample problem will be used to demonstrate how track reliability is employed.

4.4 Application of the Model

The probabilistic model was programed in FORTRAN 63 to be run on the CDC 1604 computer. Summary flow charts and a program listing are included in Appendices III and IV. The logic of the program can best be shown using the set of diagrams in figures 6 through 11.

For illustration purposes assume that in the initial orbit of the satellite, the set of position reports $P_{1,3}$ is obtained. Since there are no previous points with which this set can be correlated, they are retained in the model as uncorrelated positions. After the second sweep of the area a new set of positions $P_{2,3}$ is recorded. It is determined that each of the points in the set $P_{2,3}$ is within the radius S_{mx} of each of the previously uncorrelated points in set $P_{1,3}$. Figure 6 shows the nine possible tracks which must be considered.



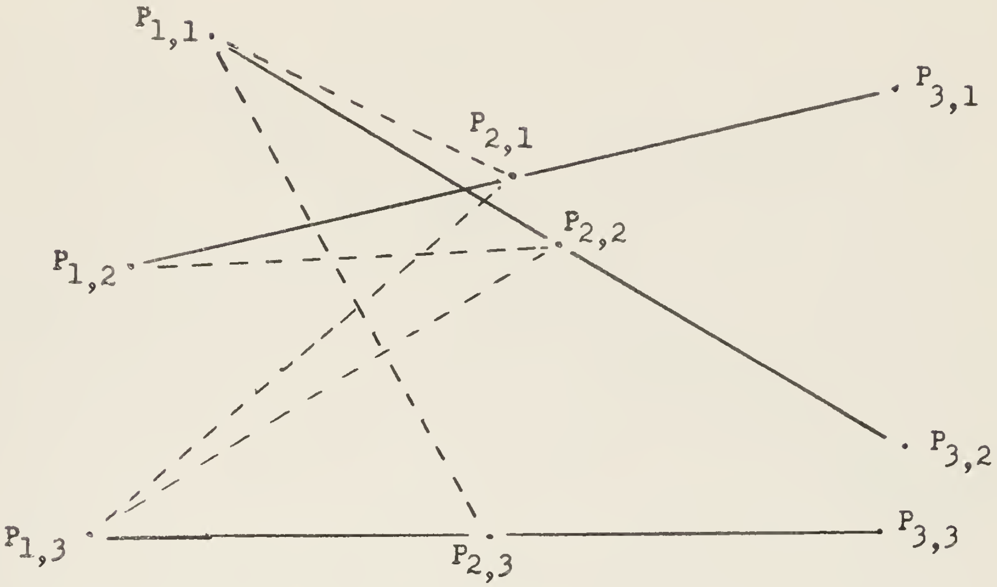
Initial Tentative Tracks

Figure 6

A value of $P(E_1)$ is computed for each of the nine possible tracks and all nine are retained until the next sweep.

At the third sweep a new set of position reports $P_{3,3}$ are received and the selection rule of consistent velocity can be applied. As before, all positions from the set $P_{3,3}$ which fall within the S_{mx} radius of the positions in $P_{2,3}$ are considered possible extensions of the nine tracks

established in sweep 2, and $P(E_1)$ is computed for each. In this track extension phase the probability $p_{s\theta}$ can be used instead of p_c which was used in the previous phase.



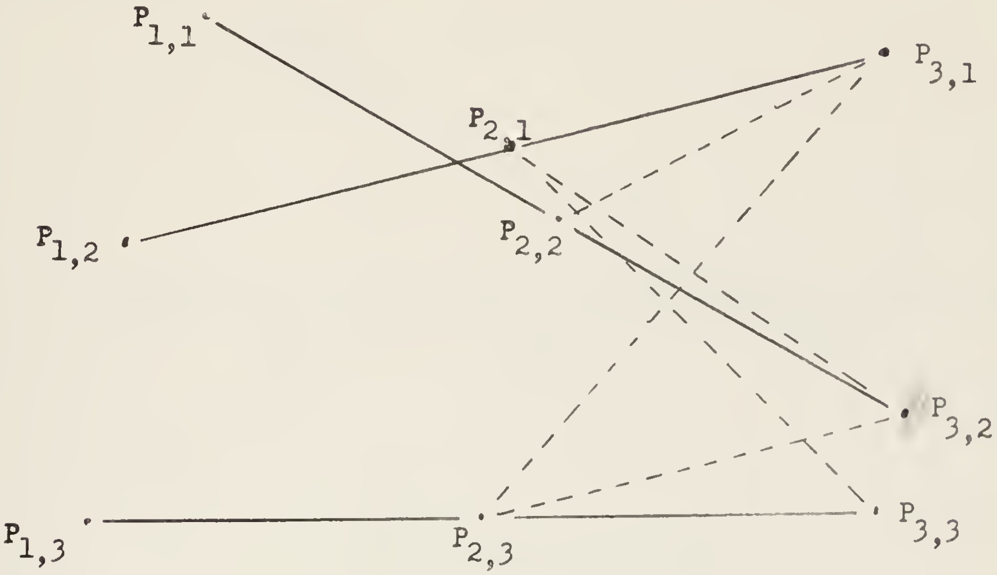
Most Likely Tracks

Figure 7

In Figure 6 the most probable tracks are indicated by the solid lines. Utilizing the selection rule of consistent velocity to extend tracks the correlation $(p_{1,3}\ p_{2,3}\ p_{3,3})$ has a higher track reliability factor than any other combination involving $p_{1,3}$. Hence $(p_{1,3}\ p_{2,1})$ and $(p_{1,3}\ p_{2,2})$ are discarded. By the same reasoning $(p_{1,1}\ p_{2,1})$, $(p_{1,1}\ p_{2,3})$, $(p_{1,2}\ p_{2,2})$, and $(p_{1,2}\ p_{2,3})$ are eliminated. Only three of the tracks produced by the position reports from sweeps 1 and 2 remain.

The possibility that $(p_{1,1}\ p_{2,2})$ represents an initial track with a course and speed change to produce the track $(p_{1,1}p_{2,2}p_{3,3})$ must also be considered when extending tracks from $P_{1,3}$ to $P_{3,3}$. The new possible

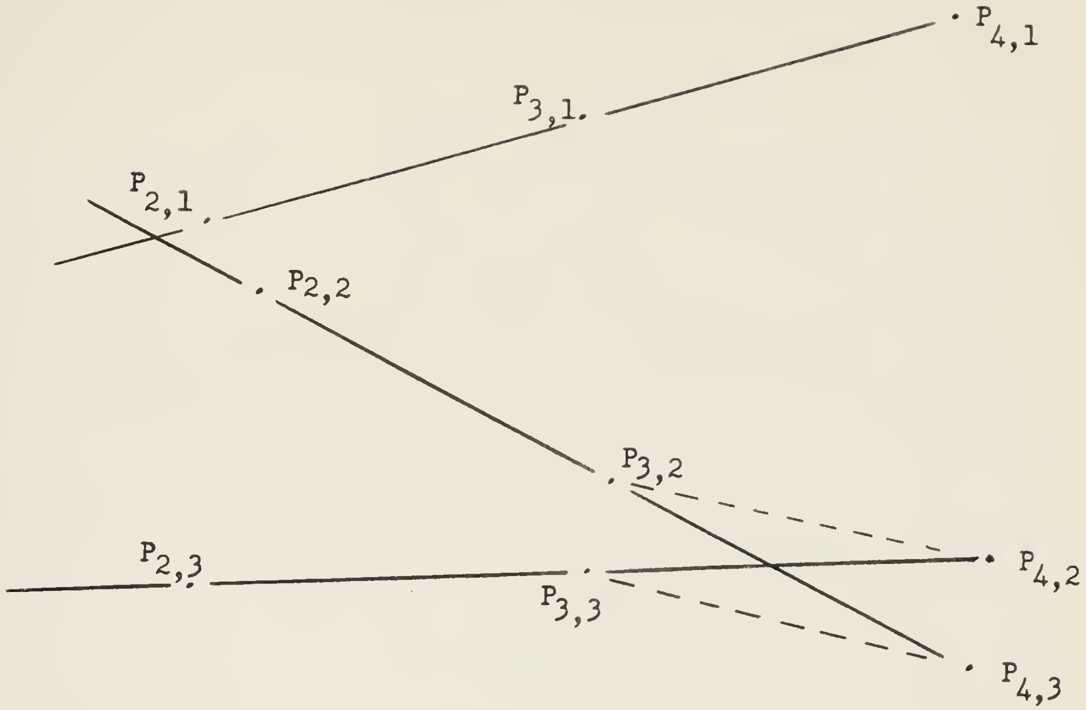
track extensions from $P_{1,3}$ to $P_{2,3}$ to $P_{3,3}$ due to "near" constant velocity alone are illustrated in figure 8 by solid lines while those tracks possible due to a speed and course change are illustrated by a combination of solid and dashed lines.



Tentative Extensions of Most Likely Tracks

Figure 8

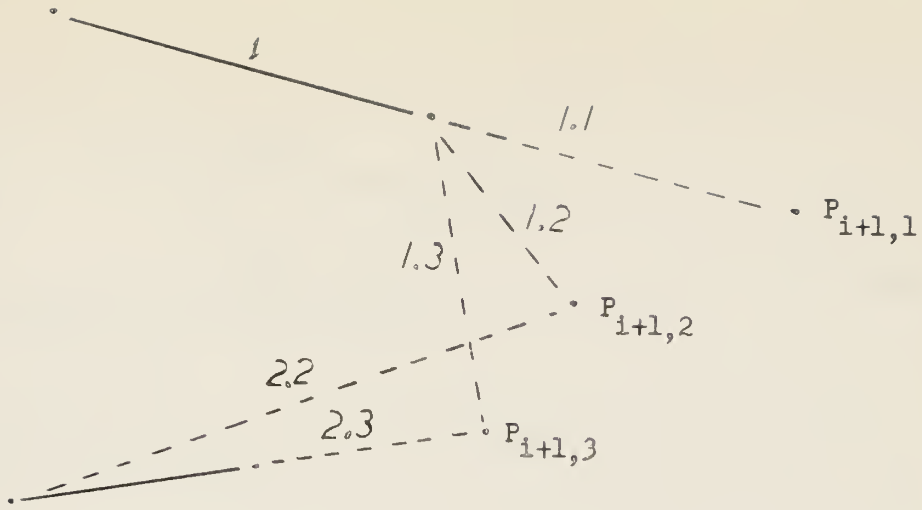
For the tracks in figure 8 the solid lines receive a higher reliability factor than do the solid - dashed combinations. Figure 9 illustrates the next phase of extension where the possible tracks are correlated with the elements from $P_{4,3}$. From the new set $P_{4,3}$ the probabilistic model has assigned only two tentative track extensions which will be used in the next phase of track extension.



Firm Track Established

Figure 9

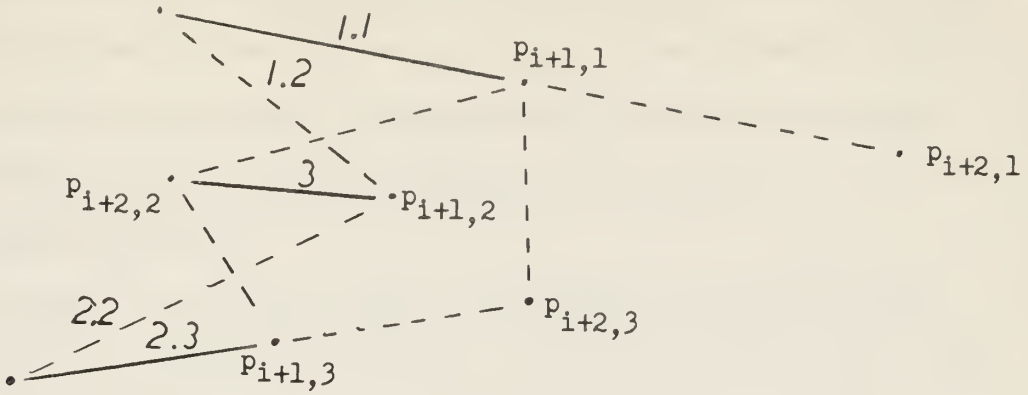
In the foregoing example tracks were initiated by the correlation of position reports from the current set $P_{i+1,n}$ with uncorrelated positions from the set $P_{i,m}$. This type of track initiation will occur in the first few orbits of the surveillance satellite and may possibly occur at any time later. A much more likely situation in later orbits is that in which the position from the new set $P_{i+1,n}$ which represents a ship which has just put to sea will be considered as a possible extension for one or more established tracks. It would not then be carried over to the next sweep as an uncorrelated position report.



Track Split

Figure 10

In figure 10 two tracks are shown, each with three possible extensions. One of the points from the set $P_{i+1,n}$ must be a position report for a ship which has just put to sea. The decision as to which of the positions represents the new track is postponed until the next sweep. Figure 11 includes the position reports from the set $P_{i+2,3}$. After computation of $P(E_1)$ for each of the possible extensions, track 1.1 extended to $p_{i+2,1}$ is determined to be the most likely extension of track 1, and track 2.3 extended to $p_{i+2,3}$ the most likely extension of 2. This leaves the correlation ($p_{i+1,2}$ $p_{i+2,2}$) as the new track.



New Track Initiated by Track Splitting

Figure 11

The track correlation problem for the probabilistic model as illustrated in figures 6 through 11 is, of course, for the particular sets, $P_{i,n}$. However consideration of these figures should give a basic understanding of the model.

The correlation process is a matter of examining three consecutive sets of position reports to select a most likely combination of positions. All but the most likely combinations involving the earliest position reports are eliminated. However, in going from one track extension phase to another all combinations involving the last two sets of position reports are retained in the model. It should be noted that the elimination of the least likely backward extension is the equivalent of establishing the track's identity with respect to tracks previously established. If a track cannot be identified with a previous track, it must be assigned a new designation and considered to be a ship which has just come under surveillance. It should also be noted that retention of only the most recent position report together with a velocity vector is

the equivalent of retaining the last two position reports and a predicted position for the next sweep. Thus, an identification symbol, a last known position, and a velocity vector provide the necessary and sufficient information for tracking in this model.

4.5 Tests and Results

In order to test this model a CDC FORTRAN 63 program labeled TRACK IV was constructed to conform to the logic of the model. This program and associated flow charts are included in Appendices III and IV. Another FORTRAN 63 program was developed in order to supply initial test data to TRACK IV. This input program is called READOUT and is included in Appendix III.

The only formal tests imposed on the model involved variations on the situation shown in figure 12. While the results of these tests provide a basis for qualitative observations there was insufficient time to impose the variety and quantity of problems required for a quantitative analysis.

The situation illustrated by figure 12 involved three tracks converging to an area and changing course when in close proximity. At about the time of course change for the three original tracks two new tracks were introduced. This problem was posed to TRACK IV on ten different runs with the interval between sweeps varying from one to twelve hours. Tabulated results of these runs are shown in table 13.

"Time to Resolve" is measured from time 64 when the problem became critical until the time when all tracks had been firmly identified and all course changes had been properly recorded.

The column entitled "Tracks Correctly Extended All Orbits" applies to tracks properly initiated and correctly tracked without loss of

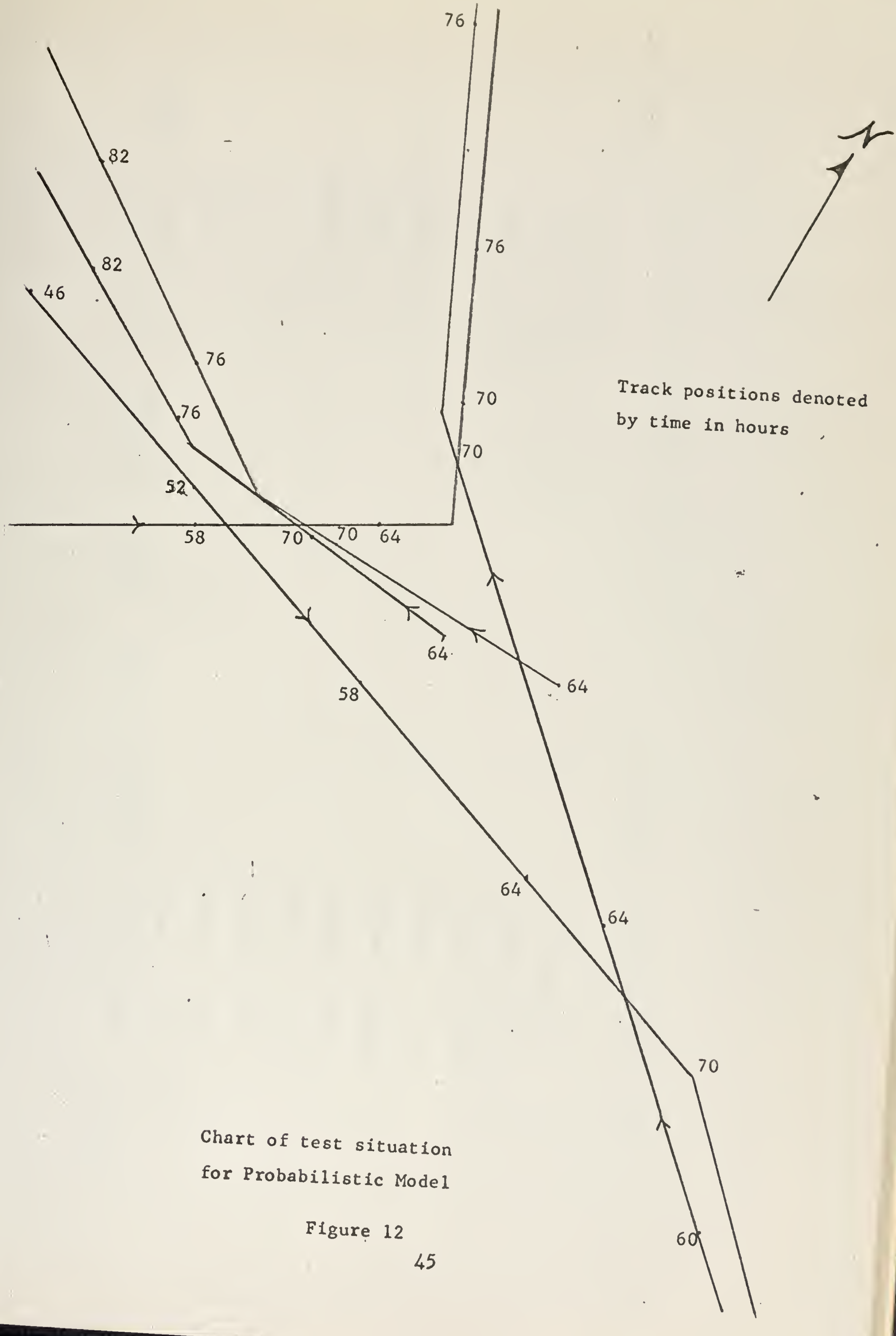


Chart of test situation
for Probabilistic Model

Figure 12

Interval	Time To Resolve	Tracks Correctly Extended All Orbits	Changed Identity	Improper Extensions	Time to Resolve New Tracks	False Tracks
1	7 hrs. 8 sweeps	4	1	0	4 hrs. 5 sweeps	1
2	10 hrs. 6 sweeps	3	4	0	6 hrs. 4 sweeps	0
3	12 hrs. 5 sweeps	4	3	0	12 hrs. 5 sweeps	0
4	12 hrs. 4 sweeps	2	2	1	4 hrs. 2 sweeps	1
5	15 hrs. 4 sweeps	1	1	2	5 hrs. 2 sweeps	1
6	18 hrs. 4 sweeps	2	2	0	6 hrs. 2 sweeps	0
7	14 hrs. 3 sweeps	3	1	1	7 hrs. 2 sweeps	0
8	16 hrs. 3 sweeps	1	1	1	8 hrs. 2 sweeps	0
10	10 hrs. 2 sweeps	4	1	0	10 hrs. 2 sweeps	0
12*	not resolved	2	0	0	not resolved	0

*Note: On the twelve hour interval test only four sweeps were made for the whole problem.

Table 13

identity throughout the whole of the problem. Improper tentative extensions may appear on any particular sweep with a higher track reliability than the true extension. However, if on the next sweep the true extension is assigned the highest track reliability the track is considered to be correctly extended. It should be noted that the most common error which precluded a track from being listed as correctly extended was that at some point the track was redesignated. In such cases the track was never really lost for more than one orbit. Cases of redesignated tracks are tabulated under the next column, "Changed Identity".

An entry is made under "Changed Identity" each time such error occurred. In the entries for the two hour interval one track was redesignated three times and another track was redesignated once. All of the errors which occur in the three hour interval concerned only one track.

The column entitled "Improper Extensions" refers to cases in which a proper track jumped to assume the identity of some other valid track while the original track was either lost or assumed a new identity. This is considered to be the most serious type of error.

The column heading "Time to Resolve New Tracks" refers to the two tracks introduced midway in the problem. The time is measured from the first appearance of the positions representing them until TRACK IV holds them as identified tracks with the proper extension being assigned the highest reliability.

The last column lists those occasions where track designations were assigned to a group of possible correlations none of which were correct. On all three of the occurrences listed, the false tracks were

dropped on the next sweep.

Another type of error was discovered in the tests which is not tabulated. In the one and two hour sweep interval runs, a number of tracks appeared which were duplicates of other firm tracks. This is due to a shortcoming of the program, TRACK IV, and is not a consequence of the logic of the model. The shortcoming is easily rectified by the addition of a sequence in the program which searches for duplicate tracks and eliminates the least likely.

4.6 Recommendations and Conclusions

The tests conducted indicate that the probabilistic model can be developed into a very useful instrument for assisting in the tracking of ships on the high seas. Only two of the shortcomings tabulated are inherent in the program logic. These are improper track extensions and the originating of false tracks. The latter is not considered serious because in each case the false track was in the system for only one sweep. Improper track extension occurs when at a particular read-out the inter-relationship between position reports indicates that two ships are making improbable course and speed changes. This fault can never be completely eliminated from the model but implementing some of the recommendations to follow may greatly reduce the frequency of occurrence.

As a result of the tests conducted the following modifications should be made to TRACK IV before further tests are undertaken.

1) More sophisticated programing methods should be employed in constructing the correlation lists. In the present model a maximum of 29 correlations can be tabulated for each track. The number of possible correlations increases as the square of the number of tracks

in an area of congestion. Thus in its present form TRACK IV reaches a saturation level when 5 tracks converge.

2) An internal track strength indicator should be assigned to each track. This can be a simple tally of the number of times a track is successfully extended. The track strength indicator will be used in connection with the next two recommendations.

3) In its present form TRACK IV computes course change and speed change by taking the difference between those indicated by the last two positions and the last course and speed. This is accurate only if the ship changed course at precisely the time of the last position report, a very unlikely event. The result is that any course change appears as a simultaneous course and speed change neither of which are correct. This reduces the track reliability to a level far below what it should be, and probably is the cause of most cases of changed identity and improper extensions. A routine should be added to TRACK IV so that when track strength indicates that the track has been successfully extended a minimum of perhaps three times and a course change is indicated with a simultaneous reduction in speed, the speed will be assumed to have remained constant and the exact amount of the course change computed by solving a triangle with the law of cosines.

4) Identity changes occur because of a shortcoming in that part of TRACK IV which eliminates the least likely backward extension of tracks previously listed as tentative. It is conceivable that all possible extensions for a track appear with a higher reliability as possible extensions of other tracks. In this case all the possible track extensions carrying the proper identity are eliminated, and the proper extension of that track appears as a split for some other track.

It is then handled as a new track. This situation can be remedied by inserting a change in the sequence which handles track splitting so that the newly initiated track is compared with all tracks which have been dropped to see if it is in fact a continuation of one of them. If so and if the strength indicator of the old track was greater than three then the old track's identity and history should be adopted for the new one.

5) Track duplication occurs as a result of several procedures in TRACK IV. The best way to rectify the situation is to add a sequence at the point in the program when all new track histories have been prepared. This routine would check for duplicate firm tracks and retain only those with the highest track reliability or those with the highest strength indicator.

With the implementation of these recommendations the probabilistic model will be capable of handling much larger and more complicated problems and will yield much more reliable performance.

The most surprising result from the series of tests of TRACK IV is the effect of extending the sweep interval. If those items used as headings in table 13 are used as criteria for performance then the ten hour sweep interval appears to be the most efficient from most standpoints. However, the results of the runs for sweep intervals between two hours and eight hours indicate that the factor which affects performance is the particular relationship existing among position reports on successive sweeps rather than length of the sweep interval alone. The model will have to be tested with a large number of varying problems before any significant observations with respect to sweep interval can be made.

5. Recommendations and Conclusions

The following recommendations and conclusions are based upon the analysis of the evaluation of the proposed models.

5.1 Recommendations

The validity of the correlation models appears to warrant their further expansion and investigation to determine:

1) The effect of relaxation of the assumption that all ships on the ocean and within range of the sensor will be detected and reported. In particular, further study should attempt to ascertain the lowest blip-scan ratio that will permit an acceptable level of correct correlations.

2) The optimum size of the areas constructed about the track projections. Statistical analysis based on many random simulations should permit this determination.

3) The maximum shipping density (number of ships per unit area) that will permit an acceptable level of correct correlations under various constraints regarding the number of course and speed changes and orbit interval.

4) The effect upon the maximum shipping density of the input of externally gathered information concerning the course and speed of a specific ship.

5) Whether these models can accept data gathered and preprocessed in the manner of the Pacific Missile Range simulation and correlate the data correctly.

6) The appropriate measures of effectiveness to be applied to this model to facilitate analysis of the meaning and effect of various parameter changes.

7) The design and effectiveness of a new model combining the essential features of the models proposed in this thesis.

5.2 Conclusion

The results of the evaluation of the two models proposed in this thesis indicate that track correlation using satellite gathered information can be satisfactorily accomplished by these and by similar correlation models. It is anticipated that further refinement of these models would provide a track correlation logic with very high capability and would be of significant value in further studies of the feasibility of ocean surveillance by satellites.

BIBLIOGRAPHY

1. Test Data Division, Pacific Missile Range. Ocean Surveillance Studies, by John Bugado and Clarence Kent. April, 1964. Pacific Missile Range Technical Note No. 3285-570, T01 OCESUR F640035.

APPENDIX I

FORTRAN 63 PROGRAM-DETERMINISTIC MODEL

This appendix contains the computer program which was written to permit computer simulation and evaluation of the deterministic model. The program is written in the Control Data Corporation FORTRAN 63 computer language and the model was evaluated by computer simulations on the CDC 1604 computer. An example of the problems generated by the program and a discussion of the input and output associated with the program are contained in Appendix II.

Comment cards are used extensively in the program to explain the flow of the problem and to define the variables used. Detailed flow charts of the program logic are on file and may be obtained from the Chairman, Department of Operations Analysis, U.S. Naval Postgraduate School.

The program uses the following FORTRAN 63 library functions:

1) RANF
2) SINF
3) COSF
4) ATANF
5) SQRTF

The program compilation time is 2 minutes and 53 seconds. Computation time ranged from 8 - 18 seconds per simulation.

```
      PROGRAM TRACKING
      DIMENSION SCUS(10,5),SSPD(10,5), SX(10,5), SY(10,5),B(10,10,16),
     1A(10,5,3),T(36),TRACK(25,5),DELTAT(10),C(10,10,3),D(10,10),
     2NAMECC(10),NAMECS(10),MAGCC(10),MAGSC(10),CUS(10,5)
      COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,
     1BWIDTHC,B,NPOSIT,NUNIQC
      TYPE INTEGER TRACK,T
      TYPE REAL MAXSPD,MINSPD,MAGCC,MAGSC
C     TIME=TIME BETWEEN POSITION REPORTS.
C     DELTAT(I)=TIME BETWEEN POSITION REPORTS.  THIS IS INCLUDED IN
C     ANTICIPATION OF EXTENDING THE PROGRAM TO TEST IT WITH DIFFERENT
C     TIME INTERVALS BETWEEN COURSE AND SPEED CHANGES.
C     NPOSIT=NUMBER OF SHIPS REPORTED AT EACH REPORTING TIME.
C     NORBIT=NUMBER OF ORBITS TO BE PROCESSED.
C     NKA=NUMBER OF PHASES TO BE PROCESSED.
C     BDEPTHO=A ESTABLISHES THE ORIGINAL AREA SIZE AS + OR - A KNOTS.
C     BWIDTHO=B AND BWIDTHCO=TWOPI-B ESTABLISHES ORIGINAL AREA WIDTH AS + OR - B
C     NCYCLE INDICATES NUMBER OF TIMES AREA SIZE HAS BEEN INCREASED.
C     SIZESQ=SIZE OF THE SQUARE AREA CONTAINING THE INITIAL POSITION OF ALL SHIP
C     CUSDEV=STANDARD DEVIATION OF COURSE CHANGES.
C     SPDDEV=STANDARD DEVIATION OF SPEED CHANGES.
C     MAXSPD=MAXIMUM SPEED PERMITTED ANY SHIP.
C     MINSPD=MINIMUM SPEED PERMITTED ANY SHIP.
C     NPROB=NUMBER OF RANDOM PROBLEMS TO BE GENERATED.
C     MX AND NUNIF ARE USED IN RANDOM NUMBER GENERATING ROUTINE.
C     RANF IS A UNIFORM RANDOM NUMBER GENERATOR.
C     RNDEV63 IS A NORMAL RANDOM NUMBER GENERATOR.
C     NAMECC(K)= NUMBER OF SHIP MAKING THE K-TH COURSE CHANGE.
C     NAMECS(K)= NUMBER OF SHIP MAKING THE K-TH SPEED CHANGE.
C     NCCUS= NUMBER OF COURSE CHANGES TO BE MADE.
C     NCSPD= NUMBER OF SPEED CHANGES TO BE MADE.
C     MAGCC(L)= AMOUNT OF COURSE CHANGE L.
C     MAGSC(L)=AMOUNT OF SPEED CHANGE L.
C     TRACK(I,J)=NUMBER OF SHIP DESIGNATED AS TRACK I AT TIME J.
C     NTRACK=NUMBER OF TRACKS DESIGNATED.
C     NUNRESR=NUMBER OF ROWS OF B CONTAINING UNCORRELATED LOSITIONS.
```

```
C     NBIN=NUMBER OF SHIPS IN A GIVEN AREA.
C     LBIN=0 IMPLIES NO AREAS OCCUPIED IN CHECK OF A SPECIFIC COLUMN OR ROW.
C     JFLAG=1 INDICATES MORE THAN ONE SHIP IN A GIVEN AREA.
C     NNFLAG .GE. 1 INDICATES AT LEAST ONE DESIGNATED ELEMENT IS IN THE AREA
C     BEING EXAMINED.
C     NUNIQC=1 INDICATES THE TRACK BEING PROJECTED IS FROM A SET Q WHICH HAS
C     ONLY ONE ELEMENT.
C     NELEM=THE NUMBER OF ELEMENTS IN A GIVEN ROW OR COLUMN OF B.
C     NDELETE=1 INDICATES THAT AT LEAST ONE ELEMENT HAS BEEN REMOVED FROM SOME
C     Q BY SUBROUTINE DESIG.
C
C     SCUS(I,J) AND SSPD(I,J) INDICATE COURSE AND SPEED OF SHIP I DURING TIME
C     BETWEEN ORBIT J-1 AND J.
C     SX(I,J) AND SY(I,J) INDICATE THE X AND Y COORDINATE OF SHIP I AT TIME
C     OF ORBIT J.
C     NOTE--SCUS(I,1) AND SSPD(I,1) HAVE NO SIGNIFICANCE UNDER THIS SETUP.
C
C     INFORMATION IS PROCESSED BY PHASES WHERE PHASE 1 CONCERNS THE RELATIONS
C     BETWEEN POSITION REPORTS FROM ORBIT 1 TO THOSE FROM ORBIT 2.  PHASE 2
C     CONCERNS RELATIONS BETWEEN POSITION REPORTS FROM ORBIT 2 TO THOSE FROM
C     ORBIT 3. ETC.
C     B(I,J,K) CONTAINS THE FOLLOWING INFORMATION--
C          K=1,4 CONTAINS INFORMATION FOR PHASE 1.
C          K=5,8 CONTAINS INFORMATION FOR PHASE 2.
C          K=9,12 CONTAINS INFORMATION FOR PHASE 3.
C          K=13,16 CONTAINS INFORMATION FOR PHASE 4.
C          I REFERS TO THE NUMBER OF THE POSITON REPORT FROM ORBIT N.
C          J REFERS TO THE NUMBER OF THE POSITION REPORT FROM ORBIT N+1.
C          B(I,J,1) CONTAINS THE PHASE NUMBER.
C          B(I,J,2) CONTAINS THE SPEED REQUIRED TO GET FROM POSITION I FROM
C          ORBIT N TO POSITION J FROM ORBIT N+1.
C          B(I,J,3) CONTAINS THE COURSE REQUIRED TO GET FROM POSITION I FROM
C          ORBIT N TO POSITION J FROM ORBIT N+1.
C          B(I,J,4) CONTAINS TRACK DESIGNATION FOR CORRELATED POSITIONS.
C          SIMILAR FORMAT HOLDS FOR PHASES 2,3, AND 4.
```

```
C      ENTER CONSTANTS
C
       PI=3.1415925 $ TWOPI=6.2831853 $ PIA=7.8539816
C
C      ENTER PARAMETERS.
C
       NPOSIT=10$NORBIT=5$TIME=1.0$MX=17$NUNIF=1$NPROB=20
       SIZESQ=100.0$CUSDEV=0.5$SPDDEV=5.0$MAXSPD=35.0$MINSPD=5.0
       BDEPTHO=2.0$BWIDTHO=0.09$BWIDTHCO=6.193
       NKA=NORBIT-1 $ NQ=NKA-1
C
C      ENTER COURSES, SPEEDS, AND INITIAL POSITIONS.
C
C      GENERATE INITIAL POSITION UNIFORMLY DISTRIBUTED IN SQUARE WITH ORIGIN
C      AT X=200 , Y=200. SIZE OF SQUARE IS VARIABLE, SIZESQ.
C
  153 DO 152 NUMRUN=1,NPROB $ PRINT 134,NUMRUN,NPROB
  134 FORMAT(1H1,///,10X,22HRANDOM PROBLEM NUMBER ,I3,3X,3HOF ,I3)
      PRINT 9422,MAXSPD,MINSPD,CUSDEV,SPDDEV,SIZESQ,TIME
 9422 FORMAT(//,10X,8HMAXSPD= ,F6.2,2X,8HMINSPD= ,F6.2,2X,8HCUSDEV= ,F6.
     13,2X,8HSPDDEV= ,F5.2,2X,8HSIZESQ= ,F6.2,2X,6HTIME= ,F4.2)
 1001 MX=MX+5
      DO 150 I=1,MX
  150 S=RANF(-1)
      DO 151 I=1,MX
  151 NUNIF=NUNIF+10
 1000 DO 107 IA=1,NPOSIT
      SX(IA,1)=RANF(-1)*SIZESQ+200.0$SY(IA,1)=RANF(-1)*SIZESQ+200.0
  107 CONTINUE
C
C      GENERATE INITIAL COURSE UNIFORMLY FROM 0 TO TWOPI.
C
      DO 108 IA=1,NPOSIT $ ACUS=RANF(-1)
      DO 108 JA=1,NORBIT $ SCUS(IA,JA)=ACUS*TWOPI
  108 CONTINUE
```

```
C     GENERATE INITIAL SPEED FROM NORM(15,SPDDEV), SUCH THAT SSPD GE 5 AND LT 35
C
      DO 109 IA=1,NPOSIT
  110 CALL RNDEV63(NUNIF,DEV)
      DEV=DEV*SPDDEV+15.0
      IF(DEV.LT.MINSPD) 110,111
  111 IF(DEV.GE.MAXSPD)110,112
  112 DO 109 JA=1,NORBIT
      SSPD(IA,JA)=DEV
  109 CONTINUE
C
C     FOR EACH TIME PERIOD SUBSEQUENT TO ORBIT 2 GENERATE THE NUMBER OF COURSE
C     AND SPEED CHANGES TO BE MADE(UNIFORM(2,8)). THEN DETERMINE WHICH SHIPS
C     MAKE THE CHANGES AND THE MAGNITUDE THEREOF.
C
      DO 113 J=3,NORBIT
      DO 118 K=1,NPOSIT
      NAMECC(K)=-0
      NAMECS(K)=-0
  118 CONTINUE
      NCCUS=RANF(-1)*7.0+2.0
      NCSPD=RANF(-1)*7.0+2.0
      DO 114 K=1,NCCUS
  117 NAMECC(K)=RANF(-1)*10.0+1.0
      DO 115 KA=1,K
      IF(KA.EQ.K) 115,116
  116 IF(NAMECC(KA).EQ.NAMECC(K))117,115
  115 CONTINUE
  114 CONTINUE
      DO 119 K=1,NCSPD
  122 NAMECS(K)=RANF(-1)*10.0+1.0
      DO 120 KA=1,K
      IF(KA.EQ.K) 120,121
  121 IF(NAMECS(KA).EQ.NAMECS(K)) 122,120
  120 CONTINUE
  119 CONTINUE
```

```
      DO 123 L=1,NCCUS
  124 CALL RNDEV63(NUNIF,DEV)
      MAGCC(L)=DEV*CUSDEV
      IF(MAGCC(L).GT.PI) 124,123
  123 CONTINUE
      DO 125 L=1,NCSPD
      CALL RNDEV63(NUNIF,DEV)
      MAGSC(L)=DEV*SPDDEV
  125 CONTINUE
      DO 126 IQ=1,NCCUS
      IN=NAMECC(IQ)
      DO 126 JQ=J,NORBIT
      SCUS(IN,JQ)=SCUS(IN,J-1)+MAGCC(IQ)
  126 CONTINUE
      DO 128 IQ=1,NCSPD
      IN=NAMECS(IQ)
      DO 128 JQ=J,NORBIT
      SSPD(IN,JQ)=SSPD(IN,J-1)+MAGSC(IQ)
      IF(SSPD(IN,JQ).LT.MINSPD) 130,131
  130 SSPD(IN,JQ)=MINSPD
      GO TO 128
  131 IF(SSPD(IN,JQ).GE.MAXSPD) 132,128
  132 SSPD(IN,JQ)=MAXSPD-0.1
  128 CONTINUE
      PRINT 133,J,NCCUS,NCSPD
  133 FORMAT(//,10X,3HJ= ,I3,5X,26HNUMBER OF COURSE CHANGES= ,I3,5X,25HN
     1UMBER OF SPEED CHANGES= ,I3)
  113 CONTINUE
```

```
C     COMPUTE POSITS FOR ALL SHIPS FOR ALL ORBITS
C
  141 DO 1003 I=1,NPOSIT
      DO 1003 J=2,NORBIT
      DELTAT(I)=TIME
 1061 IF(SCUS(I,J).LT.0.0)1060,1052
 1060 SCUS(I,J)=SCUS(I,J)+TWOPI
      GO TO 1061
 1052 IF(SCUS(I,J).GE.TWOPI) 1050,1051
 1050 SCUS(I,J)=SCUS(I,J)-TWOPI
      GO TO 1052
 1051 SC=PIA-SCUS(I,J)
      IF(SC.GE.TWOPI) 1053,1054
 1053 SC=SC-TWOPI
 1054 SX(I,J)=SX(I,J-1)+DELTAT(I)*SSPD(I,J)*COSF(SC)
 1003 SY(I,J)=SY(I,J-1)+DELTAT(I)*SSPD(I,J)*SINF(SC)
C
C     CONVERT COURSE FROM RADIANS TO DEGREES BEFORE PRINTING.
C
      DO 1010 I=1,NPOSIT
      DO 1010 J=1,NORBIT
 1010 CUS(I,J)=SCUS(I,J)*57.296
C
C     PRINT OUT COURSES, SPEEDS, POSITS
C
      PRINT 2000
 2000 FORMAT(///,10X,5HTRACK,10X,3HCUS,10X,3HSPD,10X,4HTIME,10X,7HX COOR
     1D,10X,7HY COORD)
      PRINT 2001,(((I,CUS(I,J),SSPD(I,J),J,SX(I,J),SY(I,J)),J=1,NORBIT)
     1,I=1,NPOSIT)
 2001 FORMAT(/,11X,1HT,I2,8X,F8.3,6X,F6.3,10X,I1,12X,F6.1,12X,F6.1)
```

```
C      ENTER ALL POSITS INTO A(I,J,K)
C
       DO 1004 JA=1,NORBIT
       DO 1004 IA=1,NPOSIT
       A(IA,JA,1)=JA*TIME
       A(IA,JA,2)=SX(IA,JA)
 1004  A(IA,JA,3)=SY(IA,JA)
C
C      ZEROIZE B(I,J,K)
C
       NK=(NORBIT-1)*4
 1007  DO 1005 IB=1,NPOSIT
       DO 1005 JB=1,NPOSIT
       DO 1005 KB=1,NK
 1005  B(IB,JB,KB)=-0.0
C
C      ZEROIZE C AND D.
C
       DO 954 IA=1,NPOSIT
       DO 954 JA=1,NPOSIT
       DO 954 KA=1,3
  954  C(IA,JA,KA)=-1.0
       DO 955 IA=1,NPOSIT
       DO 955 JA=1,NPOSIT
  955  D(IA,JA)=-1.0
       DO 3024 J=1,5
       DO 3024 I=1,25
       TRACK(I,J)=-0
 3024  CONTINUE
```

```
C     COMPUTE DISTANCE, COURSE AND SPEED FROM EACH POSITION OF ORBIT J TO
C     EACH POSITION OF ORBIT J+1 FOR J=1,NORBIT-1. ENTER IN B(IB,JB,KB)
C     IF SPEED IS LESS THAN OR EQUAL TO MAXSPD.
C
      DO 1006 J=1,NKA
      L=J+1
      DO 1006 I=1,NPOSIT
      TEMPX=A(I,J,2) $ TEMPY=A(I,J,3)
      DO 1006 K=1,NPOSIT
      DELTAX=A(K,L,2)-TEMPX
      DX=ABSF(DELTAX)
      IF((DX/TIME).LE.MAXSPD) 201,1006
  201 DELTAY=A(K,L,3)-TEMPY
      DY=ABSF(DELTAY)
      IF((DY/TIME).LE.MAXSPD)202,1006
  202 D=SQRTF(DX*DX+DY*DY)
      IF((D/TIME).LE.MAXSPD) 203,1006
  203 IF(DELTAY.GT.0.0) 2030,2031
 2030 THETA=TWOPI+ATANF(DELTAX/DELTAY)
      GO TO 2032
 2031 THETA=PI+ATANF(DELTAX/DELTAY)
 2032 IF(THETA.GE.TWOPI) 2033, 2034
 2033 THETA=THETA-TWOPI
 2034 SPEED=D/TIME$B(K,I,4*J-3)=J$B(K,I,4*J-2)=SPEED$B(K,I,4*J-1)=THETA
 1006 CONTINUE
C
C     PRINT B
C
      DO 3021 M=1,NKA
      PRINT 3023
      DO 3021 I=1,NPOSIT
      DO 3021 L=1,4
      K=4*M+L-4
 3021 PRINT 3022, (B(I,J,K),J=1,NPOSIT)
 3022 FORMAT(/,10X,10(F8.4,2X))
 3023 FORMAT(1H1)
```

```
C     INITIATE TRACK COUNT.
C
      NTRACK=0$BDEPTH=BDEPTHO$BWIDTH=BWIDTHO$BWIDTHC=BWIDTHCO$NCYCLE=0
      NDELETE=0
C
C     CHECK FOR UNIQUE ELEMENTS IN COLUMNS AND ROWS OF ALL PHASES
C     UNTIL ONE LOOP COMPLETED WITH NO ADDITIONAL ELEMENT DELETIONS.
C
  902 NTRACKA=NTRACK
      DO 903 NP=1,NKA
  900 CALL UNIQCOL(NP)
      IF(NDELETE.EQ.0) 901,900
  901 CALL UNIQROW(NP)
      IF(NDELETE.EQ.0)903,901
  903 CONTINUE
      IF(NTRACKA.EQ.NTRACK) 951,902
  951 NUNRESR=0
      DO 952 NS=1,NKA
      CALL UNIQROW(NS)
  952 CONTINUE
      IF(NUNRESR.GT.0) 904,607
C
C     CHECK FOR POSITIVE UNDESIGNATED ELEMENTS BY COLUMNS.
C
  904 DO 906 NP=1,NKA
      L=4*NP-4
      DO 906 JB=1,NPOSIT
      NFLAG=0$NBIN=0
      DO 922 IB=1,NPOSIT
      IF(B(IB,JB,L+1).GT.0.0) 908,922
  908 IF(B(IB,JB,L+4).GT.0.0)906,945
C
C     PROJECT TO NEXT PHASE TO DETERMINE NUMBER OF AREAS OCCUPIED
C
  945 IF(NP.EQ.NKA)946,909
```

```
 946 DO 947 IC=1,NPOSIT
     IF(B(JB,IC,L-3).GT.0.0)948,947
 948 IF((ABSF(B(IB,JB,L+2)-B(JB,IC,L-2))).LE.BDEPTH)949,947
 949 IF((ABSF(B(IB,JB,L+3)-B(JB,IC,L-1))).LE.BWIDTH)972,973
 973 IF((ABSF(B(IB,JB,L+3)-B(JB,IC,L-1))).GE.BWIDTHC)972,947
 972 NBIN=NBIN+1$NBINR=IB$NBINC=IC
     IF(B(JB,IC,L).GT.0.0)974,947
 974 NFLAG=1
     DO 975 IE=1,NPOSIT $ IF(IE.EQ.IB)975,976
 976 IF(B(IE,JB,L+1).GT.0.0)977,975
 977 IF((ABSF(B(IE,JB,L+2)-B(JB,IC,L-2))).LE.BDEPTH) 978,975
 978 IF((ABSF(B(IE,JB,L+3)-B(JB,IC,L-1))).LE.BWIDTH)906,979
 979 IF((ABSF(B(IE,JB,L+3)-B(JB,IC,L-1))).GE.BWIDTHC)906,975
 975 CONTINUE
 947 CONTINUE$ GO TO 922
 909 DO 907 IC=1,NPOSIT
     IF(B(IC,IB,L+5).GT.0.0) 911,907
 911 IF((ABSF(B(IB,JB,L+2)-B(IC,IB,L+6))).LE.BDEPTH)912,907
 912 IF((ABSF(B(IB,JB,L+3)-B(IC,IB,L+7))).LE.BWIDTH)913,9120
9120 IF((ABSF(B(IB,JB,L+3)-B(IC,IB,L+7))).GE.BWIDTHC)913,907
 913 NBIN=NBIN+1
     NBINRA=IB $ NBINRB=IC $ IF(B(IC,IB,L+8).GT.0.0) 916,907
 916 NFLAG=1
C
C    CHECK FOR ANY OTHER PAIR PROJECTING TO THE SAME DESIGNATED ELEMENT.
C    IF SO LEAVE UNRESOLVED AND CONTINUE TO NEXT ROW
C
     DO 9070 IE=1,NPOSIT $ IF(IE.EQ.JB)9070,917
 917 IF(B(IB,IE,L+1).GT.0.0)919,9070
 919 IF((ABSF(B(IB,IE,L+2)-B(IC,IB,L+6))).LE.BDEPTH) 920,9070
 920 IF((ABSF(B(IB,IE,L+3)-B(IC,IB,L+7))).LE.BWIDTH)9220,9200
9200 IF((ABSF(B(IB,IE,L+3)-B(IC,IB,L+7))).GE.BWIDTHC)9220,9070
9220 NBIN=NBIN+1 $ GO TO 922
9070 CONTINUE
 907 CONTINUE
 922 CONTINUE
```

```
C     IF ONLY ONE AREA FOUND OCCUPIED BY COLUMN CHECK, THEN CHECK THE
C     ROW CONTAINING THAT ELEMENT TO SEE IF ANY OTHER ELEMENT COULD
C     PROJECT TO SAME AREA. IF SO, CANNOT RESOLVE, GO TO NEXT COLUMN.
C
      IF(NBIN.EQ.1)210,906
  210 IF(NP.EQ.NKA) 211,910
  211 IC=NBINC $ IB=NBINR
      DO 212 ID=1,NPOSIT
      IF(B(ID,IC,L-3).GT.0.0)213,212
  213 IF(ID.EQ.JB)212,214
  214 DO 215 IG=1,NPOSIT
      IF(B(IG,ID,L+1).GT.0.0)216,215
  216 IF((ABSF(B(ID,IC,L-2)-B(IG,ID,L+2))).LE.BDEPTH) 217,215
  217 IF((ABSF(B(ID,IC,L-1)-B(IG,ID,L+3))).LE.BWIDTH)906,219
  219 IF((ABSF(B(ID,IC,L-1)-B(IG,ID,L+3))).GE.BWIDTHC)906,215
  215 CONTINUE
  212 CONTINUE
  220 CALL PROJECT(IB,JB,NP)
      GO TO 938
  910 IC=NBINRB $ IB=NBINRA
      DO 9140 ID=1,NPOSIT
      IF(B(IC,ID,L+5).GT.0.0)915,9140
  915 IF(ID.EQ.IB) 9140,923
  923 DO 914 IG=1,NPOSIT
      IF(B(ID,IG,L+1).GT.0.0) 924,914
  924 IF((ABSF(B(ID,IG,L+2)-B(IC,ID,L+6))).LE.BDEPTH)925,914
  925 IF((ABSF(B(ID,IG,L+3)-B(IC,ID,L+7))).LE.BWIDTH)906,9250
 9250 IF((ABSF(B(ID,IG,L+3)-B(IC,ID,L+7))).GE.BWIDTHC)906,914
  914 CONTINUE
 9140 CONTINUE
      IF(NFLAG.EQ.1) 926,927
```

```
C      DESIGNATE AND REMOVE OTHER ELEMENTS FROM ROW AND COLUMN OF
C      DESIGNATED ELEMENTS.
C
  926 N=B(IC,IB,L+8)$TRACK(N,NP)=JB$B(IB,JB,L+4)=N
      DO 928 IK=1,NPOSIT
      IF(B(IK,JB,L+1).GT.0.0) 929,928
  929 IF(IK.EQ.IB) 928,930
  930 DO 9280 IL=1,4
      B(IK,JB,L+IL)=-0.0
 9280 CONTINUE
  928 CONTINUE
      DO 931 IK=1,NPOSIT
      IF(B(IB,IK,L+1).GT.0.0) 932,931
  932 IF(IK.EQ.JB) 931,933
  933 DO 9130 IL=1,4
      B(IB,IK,L+IL)=-0.0
 9130 CONTINUE
  931 CONTINUE $ GO TO 938
C
C      DESIGNATE AND PROJECT.
C
  927 CALL PROJECT(IC,IB,NP)
  938 NTRACKA=NTRACK
      DO 934 NT=1,NKA
  935 CALL UNIQCOL(NT)
      IF(NDELETE.EQ.0) 936,935
  936 CALL UNIQROW(NT)
      IF(NDELETE.EQ.0) 934,936
  934 CONTINUE
      IF(NTRACKA.EQ.NTRACK) 906, 938
  906 CONTINUE $ ASSIGN 606 TO NEXTD
  605 NUNRESR=0
      DO 953 NS=1,NKA
      CALL UNIQROW(NS)
  953 CONTINUE
      IF(NUNRESR.GT.0)950,607
```

```
C     POSITS MAY BE UNCORRELATED AT THIS POINT FOR SEVERAL REASONS.
C     CASE ONE--TWO OR MORE PAIR FROM ALL OF PHASE I PROJECT TO A COMMON
C     PAIR IN PHASE I+1.
C     CASE TWO--TWO OR MORE PAIR FROM A SPECIFIC COLUMN OF PHASE I PROJECT TO A
C     PAIR IN PHASE I+1.
C     CASE THREE-ONE PAIR FROM PHASE I PROJECTS TO TWO OR MORE PAIR IN PHASE I+1
C     CASE FOUR--NO PAIR FROM A SPECIFIC COLUMN FROM PHASE I PROJECTS TO A PAIR
C     IN PHASE I+1.
C
C     CASES ONE, TWO, THREE ARE NOT MUTUALLY EXCLUSIVE.
C
  950 GO TO NEXTD
  606 DO 990 NNP=1,NQ
      DO 410 IZ=1,NPOSIT $ DO 410 JZ=1,NPOSIT
      D(IZ,JZ)=-1.0$ DO 410 KZ=1,3
  410 C(IZ,JZ,KZ)=-1.0
      L=4*NNP-4 $ MMP=NNP+1$ KFLAG=1
      DO 990 JB=1,NPOSIT
      LBIN=0 $ NNFLAG=0
  985 DO 992 IB=1,NPOSIT
      JFLAG=0 $ NFLAG=0
      IF(B(IB,JB,L+1).GT.0.0) 961,992
  961 NBIN=0
C
C     CHECK FOR AREA OCCUPANCY IN NEXT PHASE.
C
      DO 993 IC=1,NPOSIT
      IF(NFLAG.GT.0)9971,9620
 9620 IF(B(IC,IB,L+5).GT.0.0) 963,993
  963 IF((ABSF(B(IB,JB,L+2)-B(IC,IB,L+6))).LE.BDEPTH) 964,993
  964 IF((ABSF(B(IB,JB,L+3)-B(IC,IB,L+7))).LE.BWIDTH) 965,966
  966 IF((ABSF(B(IB,JB,L+3)-B(IC,IB,L+7))).GE.BWIDTHC) 965,993
  965 NBIN=NBIN+1
      IF(B(IC,IB,L+8).GT.0.0) 967,9669
  967 NFLAG=1
      IF(B(IB,JB,L+4).GT.0.0)990,9669
```

```
C      NFLAG=1 IMPLIES CASE I EXISTS.  CASE II OR CASE III MAY EXIST BUT NOT
C      KNOWN YET.
C      IF NBIN GT 1, WE MUST USE ARRAY D. CASE III EXISTS.
C      C(I,J,K) CONTAINS THE FOLLOWING INFORMATION--
C         I INDICATES SHIP NUMBER FOR PHASE N+1.
C         J INDICATES SHIP NUMBER FOR PHASE N.
C         K=1 INDICATES DISTANCE FROM POSITION OF SHIP C(I,J,2) AT ORBIT N+2 TO
C         CENTER OF BIN PROJECTED FROM RELATION BETWEEN SHIP J AT ORBIT N AND
C         SHIP I AT ORBIT N+1.
C         K=2 INDICATES SHIP NUMBER FOR PHASE N+2.
C         K=3 INDICATES DESIGNATION IF TRACK PREVIOUSLY DESIGNATED.
C      D(I,J) CONTAINS THE FOLLOWING INFORMATION--
C         I INDICATES SHIP NUMBER FOR PHASE N+2.
C         J INDICATES SHIP NUMBER FOR PHASE N+1.
C      D(I,J) INDICATES DISTANCE FROM POSITION OF SHIP JB AT ORBIT N TO
C         CENTER OF AREA PROJECTED FROM RELATION BETWEEN SHIP J AT ORBIT N+1 AND
C         SHIP I AT ORBIT N+2.
C
 9669 IF(NBIN.GT.1) 9671,9670
 9670 DIST=DISTBIN(IB,JB,IC,L)$IF(C(IB,JB,2).GT.0.0)9678,9674
 9678 JFLAG=1
 9672 IF(DIST.GE.C(IB,JB,1)) 9671,9674
 9674 C(IB,JB,1)=DIST$C(IB,JB,2)=IC$C(IB,JB,3)=B(IC,IB,L+8)
      IF(B(IC,IB,L+8).GT.0.0) 9677,9671
 9671 DIST=DISTBIN(IB,JB,IC,L)
 9676 D(IC,IB)=DIST
```

```
C      CHECK ROW IB OF PHASE I TO SEE IF ANY OTHER PAIR PROJECT TO B(IC,IB,-)
C      OF PHASE I+1.
C
 9677 DO 994 IE=1,NPOSIT$IF(IE.EQ.JB) 994,9680
 9680 IF(B(IB,IE,L+1).GT.0.0) 968,994
  968 IF((ABSF(B(IB,IE,L+2)-B(IC,IB,L+6))).LE.BDEPTH) 969,994
  969 IF((ABSF(B(IB,IE,L+3)-B(IC,IB,L+7))).LE.BWIDTH) 971,970
  970 IF((ABSF(B(IB,IE,L+3)-B(IC,IB,L+7))).GE.BWIDTHC) 971,994
  971 DIST=DISTBIN(IB,IE,IC,L)$IF(C(IB,IE,2).GT.0.0)9713,9712
 9713 JFLAG=1
 9710 IF(DIST.GE.C(IB,IE,1))993,9712
 9712 C(IB,IE,1)=DIST$C(IB,IE,2)=IC$C(IB,IE,3)=B(IC,IB,L+8)
  994 CONTINUE
  993 CONTINUE
      IF(NBIN.GT.0) 9971,991
 9971 LBIN=LBIN+1
  991 NNFLAG=NNFLAG+NFLAG
  992 CONTINUE$IF(LBIN.EQ.0)990,9921
 9921 IF(NNFLAG.GE.1)9924,9945
C
C      RESOLVE FOR THOSE ELEMENTS PROJECTING TO A DESIGNATED ELEMENT.
C
 9924 DO 9930 IV=1,NPOSIT$DO 9934 JV=1,NPOSIT
      IF(C(IV,JV,3).GT.0.0) 9970,9934
 9934 CONTINUE$GO TO 9930
 9970 LX=JV$TEMDA=C(IV,LX,1)$JX=JV$DO 9932 JW=LX,NPOSIT
      IF(C(IV,JW,1).GE.0.0)9935,9932
 9935 IF(TEMDA.LE.C(IV,JW,1))9932,9933
 9933 TEMDA=C(IV,JW,1) $ JX=JW
 9932 CONTINUE
C
C      C(IV,JX,1) HAS SMALLEST DISTANCE TO CENTER OF PROJECTED AREA. DESIGNATE IT
C
      KFLAG=1$ICC=C(IV,JX,2)$CALL DESIG(MMP,IV,ICC,JX)
      ASSIGN 9930 TO NEXTA$MI=IV$MJ=JX$MIC=ICC$GO TO 400
```

```
C      REMOVE ENTRIES FROM ROWS AND COLUMNS OF C AND D FOR THOSE DESIGNATED
C      CORRELATIONS.
C
  400 DO 401 JZ=1,NPOSIT$DO 401 KZ=1,3$C(MI,JZ,KZ)=-1.0
  401 C(JZ,MJ,KZ)=-1.0$DO 406 IZ=1,NPOSIT $ DO 406 JZ=1,NPOSIT
      IF(C(IZ,JZ,2).EQ.MIC) 407,406
  407 C(IZ,JZ,1)=-1.0 $ C(IZ,JZ,2)=-1.0 $ C(IZ,JZ,3)=-1.0
  406 CONTINUE $ IF(MJ.EQ.JB)403,404
  403 DO 405 JZ=1,NPOSIT $ DO 405 IZ=1,NPOSIT
  405 D(IZ,JZ)=-1.0 $ GO TO NEXTA
  404 DO 402 JZ=1,NPOSIT $ D(MIC,JZ)=-1.0
  402 D(JZ,MI)=-1.0 $ GO TO NEXTA
 9930 CONTINUE
C
C      CHECK FOR ENTRY IN C AND D WITH LOWEST DISTANCE.  DESIGNATE IT.
C
 9945 TEMPC=MAXSPD$TEMPD=MAXSPD$LEFT=0
      DO 9936 JV=1,NPOSIT $ DO 9936 IV=1,NPOSIT
      IF(C(IV,JV,1).GE.0.0) 9937,9936
 9937 LEFT = LEFT+1
      IF(C(IV,JV,1).LT.TEMPC) 9938,9936
 9938 TEMPC=C(IV,JV,1) $ IXC=IV$ JXC=JV
 9936 CONTINUE
      DO 9939 JV=1,NPOSIT $ DO 9939 IV=1,NPOSIT
      IF(D(IV,JV).GE.0.0)9940,9939
 9940 LEFT=LEFT+1
      IF(D(IV,JV).LT.TEMPD)9941,9939
 9941 TEMPD=D(IV,JV) $ IXD=IV $JXD=JV
 9939 CONTINUE
      IF(LEFT.GT.0)9947,980
 9947 IF(TEMPC.LE.TEMPD) 9942,9943
 9942 ICC=C(IXC,JXC,2)
      CALL DESIG(MMP,IXC,ICC,JXC)
      MI=IXC $ MJ=JXC $ MIC=ICC $ ASSIGN 9945 TO NEXTA $ GO TO 400
 9943 CALL DESIG(MMP,JB,IXD,JXD)
      MI=JXD$MJ=JB$MIC=IXD$ASSIGN 9945 TO NEXTA$GO TO 400
```

```
C      C AND D ARE EMPTY.
C
  980 IF(JFLAG.EQ.0)990,985
  990 CONTINUE
C
C      ALL OF CONTACTS IN PHASE ONE-FOUR THAT WERE NOT RESOLVED BY UNIQUE
C      ELEMENT CHECKS HAVE NOW BEEN CHECKED TO RESOLVE THE CASES INVOLVING
C      AREA CONFLICTS BY COMPARING DISTANCES TO CENTER OF PROJECTED AREA.
C      THOSE POSITIONS PROJECTING TO EMPTY AREAS ARE NOT YET RESOLVED
C      INCREASE AREA SIZE AND REPEAT.
C
      NCYCLE=NCYCLE+1 $ IF(NCYCLE.LT.7)9950,9420
 9950 ASSIGN 9951 TO NEXTD $ GO TO 605
 9951 BDEPTH=2.0*BDEPTH $ BWIDTH=2.0*BWIDTH$IF(BWIDTH.GT.PI)9960,9961
 9960 BWIDTH=PI
 9961 BWIDTHC=TWOPI-BWIDTH $ GO TO 902
 9420 NCYCLE=NCYCLE-1
  607 PRINT 9421,NCYCLE,BDEPTH,BWIDTH,BWIDTHC
 9421 FORMAT(//,11X,9HNCYCLE=  ,I2,5X,9HBDEPTH=  ,F6.1,5X,9HBWIDTH=  ,
     1F9.6,5X,10HBWIDTHC=  ,F9.6)
      DO 300 N=1,NTRACK $ IF(TRACK(N,1).GT.0)301,300
  301 DO 302 NA=1,NORBIT $ IF(TRACK(N,NA).GT.0)303,302
  303 NB=NA
  302 CONTINUE $ IF(NB.LT.NORBIT)304,300
  304 DO 305 NC=1,NTRACK $ IF(NC.EQ.N)305,306
  306 IF(TRACK(NC,NB).EQ.TRACK(N,NB))307,305
  307 DO 308 ND=NB,NORBIT $ TRACK(N,ND)=TRACK(NC,ND)$TRACK(NC,ND)=-0
  308 CONTINUE
  305 CONTINUE
  300 CONTINUE
```

```
C       PRINT RESULTS
C
-  942 DO 3006 I=1,NTRACK
  3006 T(I)=I
  3002 PRINT 3003,(T(I),I=1,NTRACK)$PRINT 3007 $ DO 3009 JM=1,NORBIT
  3003 FORMAT(//,11X,5HTRACK,3X,(36(I2,1X)))
  3009 PRINT 3008,JM,(TRACK(N,JM),N=1,NTRACK)
  3007 FORMAT(/,11X,5HORBIT)
  3008 FORMAT(/,13X,I2,4X,(36(I2,1X)))
   152 CONTINUE
  3010 END



       SUBROUTINE UNIQCOL(MP)
C
C      THIS ROUTINE CHECKS B TO FIND ANY COLUMN WHICH CONTAINS ONLY ONE POSITIVE
C      ELEMENT.
C
       DIMENSION B(10,10,16),TRACK(25,5)
       COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,
      1BWIDTHC,B,NPOSIT,NUNIQC
       NDELETE=0$NUNIQC=0$L=4*MP-4
       DO 500 JB=1,NPOSIT $ M=0 $ DO 501 IB=1,NPOSIT
       IF(B(IB,JB,L+1).GT.0.0) 502,501
   502 M=M+1 $ IF(M.GT.1) 500,505
   505 N=IB
   501 CONTINUE $ IF(M.EQ.1)503,500
   503 IB=N $ IF(B(IB,JB,L+4).GT.0.0)500,504
   504 NUNIQC=1 $ CALL PROJECT(IB,JB,MP) $ NUNIQC=0
   500 CONTINUE
       RETURN
       END
```

```
      SUBROUTINE UNIQROW(MP)
C
C     THIS ROUTINE CHECKS B TO FIND ANY ROW WHICH CONTAINS ONLY ONE POSITIVE
C     ELEMENT.
C
      DIMENSION B(10,10,16),TRACK(25,5)
      COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,
     1BWIDTHC,B,NPOSIT,NUNIQC
      NDELETE=0$NUNIQC=0$L=4*MP-4
      DO 800 IB=1,NPOSIT $ M=0 $ DO 801 JB=1,NPOSIT
      IF(B(IB,JB,L+1).GT.0.0) 802,801
  802 M=M+1 $ IF(B(IB,JB,L+4).GT.0.0)800,806
  806 NUNRESR=NUNRESR+1 $ IF(M.GT.1) 800,805
  805 N=JB
  801 CONTINUE $ IF(M.EQ.1) 803,800
  803 JB=N $ IF(B(IB,JB,L+4).GT.0.0)800,804
  804 NUNIQC=1 $ CALL PROJECT(IB,JB,MP)
  800 CONTINUE $ NUNIQC=0
      RETURN
      END

      FUNCTION DISTBIN(I,J,K,L)
C
C     THIS FUNCTION COMPUTES DISTANCE FROM A SPECIFIED POSITION TO THE CENTER
C     OF THE AREA WE ARE CONCERNED WITH.
C
      DIMENSION B(10,10,16),TRACK(25,5)
      COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,BWIDTH
     1BWIDTHC,B,NPOSIT,NUNIQC
      PI=3.1415927 $ TWOPI=6.2831854
      ARG=ABSF(B(I,J,L+3)-B(K,I,L+7))
      IF(ARG.GT.PI)1,2
    1 ARG=TWOPI-ARG
    2 DISTBIN=SQRTF(B(I,J,L+2)**2+B(K,I,L+6)**2-2.0*B(I,J,L+2)*B(K,I,L+6
     1)*COSF(ARG))
      END
```

```
      SUBROUTINE PROJECT(IB,JB,MPP)
C
C     THIS ROUTINE PROJECTS AHEAD OR BACK FROM SPECIFIED CANDIDATE PAIRS OF
C     POSITION REPORTS TO DETERMINE IF AREA IS OCCUPIED IN NEXT PHASE.
C
      DIMENSION B(10,10,16),TRACK(25,5)
      COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,
     1BWIDTHC,B,NPOSIT,NUNIQC
      IP=IB$JP=JB$MPA=MPP$KFLAG=0
C
C     KFLAG=0 INDICATES PROJECTION FORWARD. KFLAG=1 INDICATES BACK.
C
  613 NBIN=0 $ L=4*MPA-4
      NELEM=0
C
C     CHECK FOR OCCUPIED AREA IN NEXT PHASE.
C
      IF(MPP.EQ.4)605,640
  640 DO 600 IC=1,NPOSIT
      IF(B(IC,IP,L+5).GT.0.0)630,600
  630 NELEM=NELEM+1
  601 IF((ABSF(B(IP,JP,L+2)-B(IC,IP,L+6))).LE.BDEPTH)602,600
  602 IF((ABSF(B(IP,JP,L+3)-B(IC,IP,L+7))).LE.BWIDTH)603,6020
 6020 IF((ABSF(B(IP,JP,L+3)-B(IC,IP,L+7))).GE.BWIDTHC)603,600
  603 NBIN=NBIN+1
      NBINR=IC $NBINC=IP
  600 CONTINUE
```

```
C      IF ONLY ONE POSITION IN AREA, THEN CHECK TO SEE IF ANOTHER TRACK
C      CAN PROJECT TO SAME POSITION.  IF NOT, DESIGNATE.
C
       IF(NBIN.EQ.1)604,631
  631  IF(NELEM.EQ.1)632,605
  632  IF(NUNIQC.EQ.1)633,605
  633  DO 634 IC=1,NPOSIT
       IF(B(IC,IP,L+5).GT.0.0)629,634
  634  CONTINUE
  629  NBINR=IC$NBINC=IP$ GO TO 611
  604  IC=NBINR
       DO 6060 ID=1,NPOSIT
       IF(B(IC,ID,L+5).GT.0.0)607,6060
  607  DO 606 IE=1,NPOSIT
       IF(B(ID,IE,L+1).GT.0.0) 608,606
  608  IF((ABSF(B(ID,IE,L+2)-B(IC,ID,L+6))).LE.BDEPTH)609,606
  609  IF((ABSF(B(ID,IE,L+3)-B(IC,ID,L+7))).LE.BWIDTH)610,6090
 6090  IF((ABSF(B(ID,IE,L+3)-B(IC,ID,L+7))).GE.BWIDTHC)610,606
  610  NBIN=NBIN+1
  606  CONTINUE
 6060  CONTINUE
       IF(NBIN.EQ.2) 611,605
  611  CALL DESIG(MPA,JP,IP,IC)
       NUNIQC=1
C
C      PROJECT TO LAST PHASE.
C
  652  MPA=MPA+1
       IF(MPA.EQ.NKA) 605,612
  612  IP=NBINR $ JP=NBINC
       GO TO 613
```

```
C      IF PHASE GREATER THAN ONE, PROJECT BACK TO EARLIER PHASES.
C
  605 IF(MPP.GT.1) 614,615
  614 MPA=MPP $ IP=IB $ JP=JB $ KFLAG=1 $ NELEM=0
  628 NBIN=0 $L=4*MPA-4
      DO 616 IC=1,NPOSIT
      IF(B(JP,IC,L-3).GT.0.0)635,616
  635 NELEM=NELEM+1
  617 IF((ABSF(B(IP,JP,L+2)-B(JP,IC,L-2))).LE.BDEPTH)618,616
  618 IF((ABSF(B(IP,JP,L+3)-B(JP,IC,L-1))).LE.BWIDTH)619,6190
 6190 IF((ABSF(B(IP,JP,L+3)-B(JP,IC,L-1))).GE.BWIDTHC)619,616
  619 NBIN=NBIN+1 $ NBINR=JP$NBINC=IC
  616 CONTINUE $ IF(NBIN.EQ.1)620,636
  636 IF(NELEM.EQ.1)637,615
  637 IF(NUNIQC.EQ.1)638,615
  638 DO 639 IC=1,NPOSIT
      IF(B(JP,IC,L-3).GT.0.0)641,639
  639 CONTINUE
  641 NBINR=JP $ NBINC=IC$ GO TO 626
  620 IC=NBINC
      DO 6210 ID=1,NPOSIT
      IF(B(ID,IC,L-3).GT.0.0)622,6210
  622 DO 621 IE=1,NPOSIT
      IF(B(IE,ID,L+1).GT.0.0) 623,621
  623 IF((ABSF(B(ID,IC,L-2)-B(IE,ID,L+2))).LE.BDEPTH)624,621
  624 IF((ABSF(B(ID,IC,L-1)-B(IE,ID,L+3))).LE.BWIDTH)625,6240
 6240 IF((ABSF(B(ID,IC,L-1)-B(IE,ID,L+3))).GE.BWIDTHC)625,621
  625 NBIN=NBIN+1
  621 CONTINUE
 6210 CONTINUE $ IF(NBIN.EQ.2)626,615
  626 CALL DESIG(MPA,JP,IP,NBINC)$ NUNIQC=1 $MPA=MPA-1
      IF(MPA.EQ.1) 615,627
  627 IP=NBINR$JP=NBINC$NELEM=0$ GO TO 628
  615 NUNIQC=0 $ RETURN
      END
```

```
      SUBROUTINE DESIG(MPD,JB,IB,IC)
C
C     THIS ROUTINE DESIGNATES SPECIFIED POSITIONS AND DELETES OTHER ELEMENTS
C     FROM THE ROW AND COLUMN OF THE DESIGNATED ELEMENTS.
C
      DIMENSION B(10,10,16),TRACK(25,5)
      TYPE INTEGER TRACK
      COMMON NTRACK,TRACK,NDELETE,NKA,KFLAG,NUNRESR,BDEPTH,BWIDTH,
     1BWIDTHC,B,NPOSIT,NUNIQC
      MPA=MPD$K=0$I=IB$J=JB$L=4*MPA-4$IF(KFLAG.EQ.0)700,750
  700 IF(B(IB,JB,L+4).GT.0.0)701,702
  701 N=B(IB,JB,L+4)
      IF(B(IC,IB,L+8).GT.0.0)703,704
  703 NN=B(IC,IB,L+8)
      TRACK(NN,MPA+1)=-0
      TRACK(NN,MPA+2)=-0
      TRACK(N,MPA+1)=IB
  704 TRACK(N,MPA+2)=IC
      B(IC,IB,L+8)=N
  705 IF(K.EQ.0)706,707
  706 K=K+1$MPA=MPA+1$I=IC$J=JB$ GO TO 730
  702 IF(B(IC,IB,L+8).GT.0.0)708,709
  708 N=B(IC,IB,L+8)
      K=K+1
      GO TO 710
  709 NTRACK=NTRACK+1
      N=NTRACK
      B(IC,IB,L+8)=N
  710 TRACK(N,MPA+2)=IC
      TRACK(N,MPA+1)=IB
      TRACK(N,MPA)=JB
      B(IB,JB,L+4)=N
```

```
 730 L=4*MPA-4
     DO 731 IG=1,NPOSIT
     IF(B(I,IG,L+1).GT.0.0)732,731
 732 IF(IG.EQ.J) 731,733
 733 NDELETE=1
     DO 734 IH=1,4
     LK=IH+L$B(I,IG,LK)=-0.0
 734 CONTINUE
 731 CONTINUE
     DO 735 IG=1,NPOSIT
     IF(IG.EQ.I)735,737
 737 IF(B(IG,J,L+1).GT.0.0)738,735
 738 NDELETE=1
     DO 739 IH=1,4
     LK=IH+L$B(IG,J,LK)=-0.0
 739 CONTINUE
 735 CONTINUE
     IF(KFLAG.EQ.0)705,7050
7050 IF(K.EQ.0)7051,707
7051 K=K+1$MPA=MPA-1$I=JB$J=IC$GO TO 730
 750 IF(B(IB,JB,L+4).GT.0.0)751,752
 751 N=B(IB,JB,L+4) $ IF(B(JB,IC,L).GT.0.0)753,754
 753 NN=B(JB,IC,L) $ TRACK(NN,MPA-1)=-0 $ TRACK(NN,MPA)=-0
     TRACK(N,MPA-1)=IC $ TRACK(N,MPA)=JB $ B(JB,IC,L)=N $ GO TO 707
 754 TRACK(N,MPA-1)=IC $ B(JB,IC,L)=N
     K=K+1$MPA=MPA-1$I=JB$J=IC$GO TO 730
 752 IF(B(JB,IC,L).GT.0.0)755,756
 755 N=B(JB,IC,L) $ K=K+1 $ GO TO 757
 756 NTRACK=NTRACK+1 $ N=NTRACK
 757 TRACK(N,MPA-1)=IC $ B(JB,IC,L)=N$B(IB,JB,L+4)=N
     TRACK(N,MPA)=JB$TRACK(N,MPA+1)=IB$GO TO 730
 707 RETURN
     END
```

```
         IDENT       RNDEV63                                        00000000
         ENTRY       RNDEV63                                        00000010
RNDEV63  SLJ         **                                             00000020
         SIU     1   EXIT              SAVE INDEX                   00000030
         LIU     1   RNDEV63                                        00000040
         LDA     1   0                                              00000050
         SAL         EXIT-1            SET SECOND ARG R             00000060
         ARS         24                                             00000070
         SAU         RDVLP             SET FIRST ARG NUNIF          00000080
         SAL         RDVLP+1           SET FIRST ARG NUNIF          00000090
         INI     1   1                                              00000100
         SIL     1   EXIT              SET EXIT                     00000110
         ENA                                                        00000120
         STA         ERASE                                          00000130
         ENI     1   15                                             00000140
RDVLP    LDA         **                **=ADDRESS OF INPUT ARG      00000150
         MUI         FIVE13                                         00000160
         SCL         RDVCONS+1         REDUCE MOD2 TO THE 43RD      00000170
         STA         **                **=ADDRESS OF INPUT ARG      00000180
         RAD         ERASE                                          00000190
         IJP     1   RDVLP                                          00000200
         SUB         RDVCONS           SUBTRACT 2 TO THE 46TH       00000210
         STA         ERASE             SET FLAG                     00000220
+        AJP     2   *+1                                            00000230
         LAC         ERASE             COMPLEMENT IF NEG            00000240
+        SCA     1   2057B             FLOAT A                      00000250
         LRS         47                                             00000260
         ENA     1   0                                              00000270
         LLS         36                                             00000280
         SSK         ERASE             CHECK FOR NEGATIVE DEVIATE   00000290
         SCM         RDVCONS+3                                      00000300
```

```
          SCM       RDVCONS+3                                                  00000310
          FMU       RDVCONS+2                 DIVIDE BY STANDARD DEVIATION     00000320
          STA       **                        ** = ADDRESS OF SECOND ARG R     00000330
EXIT      ENI     1 **                                                         00000340
          SLJ       **                                                         00000350
ERASE     BSS       1                                                          00000360
FIVE13    DEC       1220703125                                                 00000370
RDVCONS   OCT       2000000000000000                                           00000380
          OCT       7600000000000000                                           00000390
          OCT       1724673317272054                                           00000400
          OCT       -0                                                         00000410
          END                                                                  00000420
          END
          FINIS
-EXECUTE.
```

APPENDIX II

INPUT AND OUTPUT - DETERMINISTIC MODEL

The variable names used by this program are defined in the program listing contained in Appendix I. No provision is made for reading the values of parameters into the program. Changes in parameter values are made by inserting punched cards into the program deck prior to compilation. The parameters which determine the formulation of the problem are:

1) NPOSIT
2) NORBIT
3) SIZESQ
4) CUSDEV
5) SPDDEV
6) MAXSPD
7) MINSPD
8) MX
9) NUNIF
10) NPROB
11) BDEPTHO
12) BWIDTHO
13) BWIDTHCO
14) TIME

The DIMENSION statement for all arrays must be changed if the value of NPOSIT exceeds 10 or if the value of NORBIT exceeds 5. The values of the other parameters may be changed freely.

The sample output which follows illustrates several points:

1) Governing parameters are printed at the beginning of the output. The number of course changes and the number of speed changes to be made for orbit J, as determined by random numbers, are indicated. A course change or speed change indicated for orbit J determines the course or speed for the period between orbit J-1 and orbit J.

2) The column labeled TRACK gives the position of each ship at the time of the orbit number listed in column TIME. The course and speed listed is the course and speed for the ship indicated for the period prior to the time of the position report.

3) The course, speed and position for each ship at the initial orbit is generated by use of random numbers. The program then determines how many changes of course and speed will be made, which ship will make them, and the sign and magnitude of the change. The later courses, speeds, and positions are then computed and used as a basis for correlation.

4) NCYCLE indicates the number of times the dimensions of the constructed areas were increased before the final correlation was made. Final dimensions are indicated.

5) The print-out of tracks indicates which ship was designated as a specified track for each orbit. Any track which contains the same ship number for all orbits is considered to be perfectly correlated. In this example Track 2 and Track 14 were erroneously projected back to orbit 1. The cause is not apparent without plotting all tracks.

6) Note that a "mistake" in correlation as indicated in this example does not necessarily imply faulty correlation logic. Many cases of this type result from crossing tracks and erratic ship maneuvering. The "correct" logic may pick the "wrong" ship.

7) The tracks containing all zeroes result from duplication of designations. For example, ship number seven may have been designated as Track 3 for orbits 3, 4, and 5. It may have been later designated as Track 6 for orbits 1, 2, and 3. The duplication is resolved prior to printing the results of the correlation.

```
RANDOM PROBLEM NUMBER    9   OF  20

MAXSPD=  35.00  MINSPD=   5.00  CUSDEV=   .500  SPDDEV=  5.00  SIZESQ= 100.00  TIME= 8.00

J=   4     NUMBER OF COURSE CHANGES=   7     NUMBER OF SPEED CHANGES=   7

J=   5     NUMBER OF COURSE CHANGES=   4     NUMBER OF SPEED CHANGES=   8

TRACK           CUS        SPD         TIME         X COORD       Y COORD
 T 1         16.603     21.636            1           217.6         237.2
 T 1         16.603     21.636            2           267.1         403.1
 T 1         16.603     21.636            3           316.5         569.0
 T 1         41.711     21.636            4           431.7         698.2
 T 1         79.990     16.693            5           563.2         721.4
 T 2         97.887     10.726            1           271.3         231.0
 T 2         97.887     10.726            2           356.3         219.2
 T 2         97.887     10.726            3           441.3         207.5
 T 2         97.887     10.726            4           526.3         195.7
 T 2         97.887     10.174            5           607.0         184.5
 T 3        253.587      9.997            1           285.1         260.4
 T 3        253.587      9.997            2           208.4         237.8
 T 3        253.587      9.997            3           131.7         215.2
 T 3        253.587      7.322            4            75.5         198.7
 T 3        253.587      5.803            5            31.0         185.6
```

T 4	6.133	22.878	1	241.4	270.5
T 4	6.133	22.878	2	261.0	452.5
T 4	6.133	22.878	3	280.5	634.4
T 4	14.151	22.878	4	325.3	811.9
T 4	333.407	22.068	5	246.3	969.8
T 5	166.081	20.000	1	247.7	231.2
T 5	166.081	20.000	2	286.2	75.9
T 5	166.081	20.000	3	324.7	-79.4
T 5	166.081	23.811	4	370.5	-264.3
T 5	166.081	31.542	5	431.2	-509.3
T 6	312.110	11.295	1	236.5	237.4
T 6	312.110	11.295	2	169.5	298.0
T 6	312.110	11.295	3	102.5	358.6
T 6	300.694	13.049	4	12.7	411.9
T 6	295.737	11.233	5	-68.3	450.9
T 7	231.023	17.960	1	265.3	209.3
T 7	231.023	17.960	2	153.6	118.9
T 7	231.023	17.960	3	41.9	28.5
T 7	221.013	15.525	4	-39.6	-65.2
T 7	210.535	15.525	5	-102.7	-172.2

```
T 8        277.753      9.238          1           216.5          291.7
T 8        277.753      9.238          2           143.2          301.7
T 8        277.753      9.238          3            70.0          311.6
T 8        307.914      8.169          4            18.5          351.8
T 8        307.914     12.435          5           -60.0          412.9
T 9        295.352     11.867          1           297.6          254.7
T 9        295.352     11.867          2           211.8          295.3
T 9        295.352     11.867          3           126.0          336.0
T 9        246.559     11.011          4            45.2          300.9
T 9        246.559     13.422          5           -53.3          258.2
T10        335.002     15.462          1           241.2          293.2
T10        335.002     15.462          2           188.9          405.3
T10        335.002     15.462          3           136.6          517.4
T10         13.547     10.949          4           157.1          602.5
T10         13.547     10.949          5           177.6          687.7

NCYCLE=   2     BDEPTH=      8.0     BWIDTH=     .360000     BWIDTHC=   5.923185

TRACK     1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17
ORBIT
   1      2  ⑥ -0 -0  4  7 -0 -0 -0 -0 10  3 -0  ⑤  9  8  1
   2      2  5 -0 -0  4  7 -0 -0 -0 -0 10  3 -0  6  9  8  1
   3      2  5 -0 -0  4  7 -0 -0 -0 -0 10  3 -0  6  9  8  1
   4      2  5 -0 -0  4  7 -0 -0 -0 -0 10  3 -0  6  9  8  1
   5      2  5 -0 -0  4  7 -0 -0 -0 -0 10  3 -0  6  9  8  1
```

APPENDIX III

FORTRAN 63 PROGRAM - PROBABILISTIC MODEL

The input to TRACK IV is a magnetic tape prepared by some program such as READOUT. This input tape may contain simulated position reports for one or more readouts. The data from one readout can contain from one to 100 position reports and must be written with a FORTRAN 'WRITE TAPE i,L' statement where L is an array dimensioned as (100,3). Each position report occupies three words of the array L as follows:

L(i,1) = Time of report

L(i,2) = Latitude of the position

L(i,3) = Longitude of the position

The array L must be TYPE REAL, that is all data must be in floating point. The data must be in the units of measurement described in the next paragraph. A problem termination is indicated on the input tape by an END OF FILE. No END OF FILE should appear between readouts.

The method and units of measurement for the quantities processed by TRACK IV are as follows:

1) Time - Time is measured in hours from the beginning of the problem to the end. Time need not begin with 0.0 for the first report. In fact, if the program READOUT is used a time less than 2.0 will not be processed. Time is a floating point quantity.

2) Latitude - Latitude is measured in radians from 0.0 radians at the north pole to π radians at the south pole. It is a floating point quantity.

3) Longitude - Longitude is measured in radians from 0.0 radians at the Greenwich meridian eastward through 2π radians. It is a floating point quantity.

4) Course - Course is measured in radians from 0.0 at north to

the right through 2π radians. It is a floating point value.

5) Speed - Speed is measured in radians per hour. It may be converted to knots by multiplying the value by 3436.6. Speed is a floating point quantity.

6) Distance - Distance is measured in radians and may be converted to nautical miles by the same conversion factor specified for converting speed to knots. It is a floating point quantity.

7) Probability - Probability is handled in two forms. In most computations it is a floating point value between zero and one. It is stored in lists by multiplying the value by 1000 and converting to integer form. This permits the quantity to occupy 12 bits in memory. Some computations in TRACK IV handle probabilities in their integer form.

TRACK IV utilizes a permanent record tape on which to store track histories between readouts. The tape also contains the next available track number and a list of any uncorrelated position reports. The format of these lists is as described below for the arrays TRACK and OLD DATA. This tape is set to an initial blank form by TRACK IV before processing the first input from the input data tape. If it is desired to continue a problem on different runs, that part of the program which initializes the permanent memory tape must be removed before the second run.

Two tape units are used by TRACK IV as temporary storage. These are identified as units two and three in the program. The input tape is designated unit one and the permanent memory tape as unit four.

Data design for TRACK IV is as follows:

1) OLD DATA and NEW DATA are arrays dimensioned (500,3) and

(100,3) respectively. Both contain position reports in the form:

NEW DATA (I,1) = time of report

NEW DATA (I,2) = latitude

NEW DATA (I,3) = longitude

2) TR LIST and TR VEL are equivalent names for the same array which is dimensioned as (31,4). Data is addressed as TR LIST if it is an integer value and as TR VEL if it is a floating point quantity.

a) TR LIST(1,1) bits 0 - 5 contain the tentative part of the track number. Bits 6 - 23 contain the basic track number. Bits 24 - 47 are unused.

b) TR LIST(1,2) bits 0 - 11 contain the probability of termination computed on the last sweep. Bits 12 - 23 contain the track reliability assigned to the track on the last sweep.

c) TR VEL(1,3) and TR VEL(1,4) contain the time of initial track contact and the time of last extension respectively.

d) TR VEL(2,1) and TR VEL(2,2) contain the latitude and longitude of the last known position respectively.

e) TR LIST(2,3) is set to 777 octal if the list concerns a previously uncorrelated position report instead of a previous track. This flag indicates that there is no history for the track.

f) TR VEL(2,3) and TR VEL(2,4) contain the last known course and speed respectively if the list concerns a previously known track.

3) The remainder of the TR VEL/TR LIST array contains possible correlation in the form:

a) TR LIST(I,1) = new data list index corresponding to the location of the position report in NEW DATA.

b) TR LIST(I,2) $p_{s\theta}$ or p_c for the correlation listed until the list is normalized; $L(Ap_{i+1,j})$ thereafter.

c) TR VEL(I,3) and TR VEL(I,4) contain course and speed respectively as indicated if this correlation is a valid one.

4) PL LIST is dimensioned (100,29) and is TYPE INTEGER; that is, data in the list is integer rather than floating point. In this array all correlations which involve a specific new position report are tabulated. Each entry requires one computer word. Bits 0 - 11 contain the p_c or $p_{s\theta}$ as appropriate until the list is normalized; $L(p_{i+1,j}A)$ thereafter. Bits 12 - 17 contain the track tentative number and bits 18 - 32 the basic track number for the track with which the position report may be correlated. Bits 33 - 47 are unused. An entry addressed as PL LIST(I,N) refers to the N^{th} possible correlation for the I^{th} entry in NEW DATA.

5) TRACK NR and TRACK are equivalent names for the same list. The list is eight computer words long. TRACK contains the permanent record form of the track history as it is stored on the permanent memory tape. If a data word in the list is an integer it is addressed as TRACK NR; if it is a floating point value it is addressed as TRACK.

a) TRACK NR(1) contains the track number and tentative number in bits 0 - 20. Bits 21 - 47 are not used.

b) TRACK NR(2) bits 0 - 11 contain the probability of termination computed at the time of the last extension. Bits 12 - 23 contain the track reliability. Bits 24 - 47 are not used.

c) TRACK(3) to TRACK(8) contain, in the order listed, time of track initiation, time of last position, latitude of last known position, longitude of last known position, last known course, and last

known speed.

Table 14 is a sample output from TRACK IV. The numeral to the left of the radix point in the track number column is the basic track number. Ideally it would remain unchanged from the time a track is initiated until the time it is terminated. The digits to the right of the radix point are branch identifiers. They are assigned at each readout to identify all possible correlations for the basic track.

Arrows to the left are not part of the print out. They were inserted by the author to show which of the possible extensions is the true one. The sample shown was the output for the test described in figure 12 for the four hour interval run.

```
                                    SEA SURVEILLANCE - PROCESSING TIME   68.000
UNCORRELATED CONTACTS
   TIME           LATITUDE            LONGITUDE


ACTIVE TRACKS
TRACK NR      1ST TIME      LAST TIME       LAT        LON         CSE       SPD    RELIABILITY


→ 3. 5        52.000        68.000        33.850     -15.266     314.211    15.43      .6340
  3. 4        52.000        68.000        33.733     -15.666     299.259    18.43      .4040
  3. 3        52.000        68.000        33.683     -15.950     292.809    21.30      .2570
  3. 2        52.000        68.000        32.766     -13.833     128.465     8.85          0
  3. 1        52.000        68.000        34.116     -15.650     312.993    21.64      .2790

  1. 5        40.000        68.000        33.850     -15.266      99.498     7.58      .2750
  1. 4        40.000        68.000        33.733     -15.666     140.285     3.90      .3170
  1. 3        40.000        68.000        33.683     -15.950     195.481     3.89      .3260
  1. 2        40.000        68.000        32.766     -13.833     124.484    30.93          0
→ 1. 1        40.000        68.000        34.116     -15.650      44.406     3.85      .5040

  4. 5        40.000        68.000        33.850     -15.266     294.282     5.48      .1730
→ 4. 4        40.000        68.000        33.733     -15.666     272.868    10.00      .6060
  4. 3        40.000        68.000        33.683     -15.950     268.941    13.53      .0320
  4. 2        40.000        68.000        32.766     -13.833     137.198    19.09          0
  4. 1        40.000        68.000        34.116     -15.650     302.656    11.59      .2710

  5. 5        40.000        68.000        33.850     -15.266      24.121     3.56      .0030
  5. 4        40.000        68.000        33.733     -15.666     292.984     3.84      .1370
→ 5. 3        40.000        68.000        33.683     -15.950     276.051     7.12      .3760
  5. 2        40.000        68.000        32.766     -13.833     123.751    23.41          0
  5. 1        40.000        68.000        34.116     -15.650     335.389     7.98      .6900

  2. 5        40.000        68.000        33.850     -15.266     322.854    16.95          0
  2. 4        40.000        68.000        33.733     -15.666     307.621    19.26          0
  2. 3        40.000        68.000        33.683     -15.950     300.329    21.80          0
→ 2. 2        40.000        68.000        32.766     -13.833     109.490     8.25      .9890
  2. 1        40.000        68.000        34.116     -15.650     319.391    23.07          0
```

Sample Output for TRACK IV

Table 14

```
C
-COOP,,MCARTHUR SURVEILLANCE,I/1/4/0/4/S/56/57/E/2=56/3=57,
-C     30, 10000, 4.
-FTN,L,E.
      PROGRAM TRACK IV
      COMMON LAT2,LAT1,LON2,LON1,TIME2,TIME1,CSE,SPD
      COMMON/A/ TRACK NR(8), TRACK(8), TR LIST(31,4), TR VEL(31,4),
     1 NEW DATA(100,3), OLD DATA(500,3), P1 LIST(100,29), DATA(500,3),
     2  DELETE(500)
      TYPE REAL NEW DATA,MU1,LAT1,LON1,LAT2,LON2,MU3,MU2
      TYPE INTEGER  TRACK NR, TR LIST, P1 LIST, DATA,PROB 1,PROB 2,
     1   PROB 3, PROB 4, DELETE
      EQUIVALENCE (TRACK NR, TRACK), (TR LIST, TR VEL),(OLD DATA,DATA)
      DATA (E = 2.71828183)
      DATA ( AVG SHIPS = 5000.0), (ARR RATE = .10)
      DATA ( SIGMA T = .004166)
      DATA(MU1 = .00404073), (SIGMA 1 = .001744)
      DATA(MU 2 = 0.000000),(SIGMA 2 = .0005814)
      DATA(MU 3 = 0.00000),(SIGMA 3 = .42)
      DATA (DEADTIME = 48.0)
C
C   SET CONSTANTS
C
      COEFF 4 = 1/( AVG SHIPS * ARR RATE)
      SQRT 2 PI = SQRTF( 2 * 3.14159)
      N12 = 2**12
      N30 = 2**30
      N24 = 2**24
```

```
C
C    INITIALIZE PERMANENT MEMORY TAPE.
C
        REWIND 4
        NEXT TN = 1
        WRITE (4) NEXT TN
        DO 1 I = 1, 500
        DO 1 J = 1, 3
      1 OLD DATA(I,J) = 0.0
        WRITE (4) OLD DATA
        END FILE 4
C
C    COMMENCE PROCESSING.
C
 9001 READ (1) NEW DATA
      IF (EOF, 1)  9002, 9006
 9002 REWIND 1
      STOP
 9006 PROCTIME = 0.0
      DO 9007 I = 1,100
      IF ( NEW DATA(I,1) .EQ. 0.0) 9009, 9008
 9008 IF (NEW DATA(I,1) .GT. PROCTIME) 9010, 9007
 9010 PROCTIME = NEW DATA(I,1)
 9007 CONTINUE
      I = 101
 9009 INDEX 3 = I - 1
      IF ( I .EQ. 1 ) 9001,  9005
 9005 REWIND 4
      REWIND 2
      REWIND 3
C
```

```
C     KEY 2 IS SET IF A STOP IS DESIRED JUST BEFORE WRITING FINAL TAPE
C     KEY 3 IS SET IF A STOP IS DESIRED BEFORE PROCESSING NEXT NEW
C     DATA
C
C
C     CLEAR P1 LIST
C
  100 DO 1011 I = 1,100
      DO 1011 J = 1, 29
 1011 P1 LIST(I,J) = 0
C
      READ(4) NEXT TN
C
C     TEST FOR OLD UNCORRELATED POINTS. IF NONE,GO TO CHECK FOR TRACKS
C
      READ (4) OLD DATA
C
C     CHECK FOR POSSIBLE CORRELATIONS
C
  101 DO 102 I=1,7
  102 TRACK NR(I)  =0
      DO 103 I = 1,31
      DO 103 J = 1,4
  103 TR LIST(I,J) = 0
C
C
      DO 104 II=1,500
      J = 3
      IF ( OLD DATA(II,1) .EQ. 0.0) 200 , 105
  105 LAT 1 = OLD DATA(II,2)
      LON1 = OLD DATA(II,3)
      TIME 1 = OLD DATA(II,1)
```

```
C     SEARCH NEW DATA
C
      DO 106 L = 1, INDEX 3
       IF (ABSF((NEW DATA(L,2) - LAT 1)/(NEW DATA(L,1) - TIME 1)) .GT.
    1       .011628) 106 ,108
  108 IF (ABSF( (NEW DATA(L,3) - LON 1)/(NEW DATA(L,1) -TIME 1) *
    1   COSF(LAT1)).GT. .011628)106, 109
C
C     HAVING DETERMINED THAT THIS NEW DATA POINT IS IN VICINITY OF
C     THIS OLD DATA POINT, PROCEDE TO CHECK CSE AND SPEED
C
  109 LAT 2 = NEW DATA(L,2)
      LON 2 = NEW DATA(L,3)
      TIME 2 = NEW DATA(L,1)
      CALL CSESPD
      IF(SPD  .GT. .011628) 106, 110
C
C     CORRELLATION IS POSSIBLE. COMPUTE PROBABILITY
C
  110 IF ( J .GT. 31) 117, 1101
  117 N = NEXT TN - 1
      PRINT 113, N
      GO TO 104
 1101 TR LIST(J,1) = L
      TR VEL(J,2) = (1/E**((((SPD - MU1)/SIGMA 1)**2)/2.0))*1000.0
      TR LIST(J,2) = TR VEL(J,2)
      TR VEL(J,4) = SPD
      TR VEL(J,3) = CSE
      TR LIST(2,3) = 777B
```

```
C
C      COPY DATA IN P1 LIST
C
       DO 112 I = 1,29
       IF (P1 LIST( L,I) .EQ. 0) 114, 112
  112  CONTINUE
       PRINT 113, L,
  113  FORMAT (1X,30HSATURATED IN VICINITY OF PT.   , I5)
       GO TO 104
  114  IF (TR LIST(1,1) .EQ. 0) 115, 116
  115  TR LIST(1,1) = NEXT TN * 64
       NEXT TN = NEXT TN + 1
       NEXT TN = NEXT TN .AND. 77777 B
       IF (NEXT TN .EQ. 0) 1151, 1152
 1151  NEXT TN = 1
 1152  TR VEL(2,1) = LAT 1
       TR VEL(2,2) =  LON 1
       TR VEL(1,4) = TIME 1
       TR VEL(1,3) = TIME 1
       TR LIST(2,4) = II
       OLD DATA(II,1) = 0.0
  116  P1 LIST(L,I) = TR LIST(1,1) * N12 + TR LIST(J,2)
       J = J+1
  106  CONTINUE
C      INCREMENT L AND LOOK AT NEXT NEW DATA POINT
       IF (TR LIST(1,1).EQ. 0) 104,119
  119  WRITE (2) TR LIST
       DO 120 J = 1,31
       DO 120 I = 1,4
  120  TR LIST(J,I) = 0
C
  104  CONTINUE
```

```
      II       = 501
C
C     COMMENCE CHECKING TRACKS FOR CORRELLATIONS
  200 INDEX O = II - 1
 2001 READ (4) TRACK
      IF (EOF,4) 300, 201
  201 LAT 1 = TRACK(5)
      LON 1 = TRACK(6)
      TIME 1 = TRACK(4)
      TR LIST(1,1) = TRACK NR(1)
      TR LIST(1,2) = TRACK NR(2)
      TR VEL(1,3)  = TRACK(3)
      TR VEL(1,4)  = TRACK(4)
      TR VEL(2,1)  = TRACK(5)
      TR VEL(2,2)  = TRACK(6)
      TR VEL(2,3)  = TRACK(7)
      TR VEL(2,4)  = TRACK(8)
      J =  3
C     SEARCH NEW DATA LIST
C
      DO 202 L = 1, INDEX 3
C
C     ROUGH CHECK ON LAT DIFFERNECE
C
      IF (  ABSF( (NEW DATA(L,2) - LAT 1)/(NEW DATA(L,1) - TIME 1))
     1   .GT. .011628 ) 202, 203
  203 IF (   ABSF(   (NEW DATA(L,3)- LON 1)/(NEW DATA(L,1)- TIME 1)
     1    *  COSF(LAT 1))             .GT. .011628 ) 202, 204
```

```
C
C     PT IS IN VICINITY OF THIS TRACK. SEE IF CORRELLATION POSSIBLE
C
  204 LAT 2 = NEW DATA(L,2)
      LON 2 = NEW DATA(L,3)
      TIME 2 = NEW DATA(L,1)
      CALL CSE SPD
      IF ( SPD .GT. .011628) 202, 205
C
C     LIST CORRELATION IN P1 LIST
C
  205 DO 206 I = 1,29
      IF (P1 LIST(L,I) .EQ. 0) 207, 206
  206 CONTINUE
      PRINT 113, L
      GO TO 202
  207 IF (J .GT. 31) 208, 211
  208 N = TRACK NR(1)
      PRINT 113, N
      GO TO 222
  211 TR LIST(J,1) =  L
      PROB 1 = (1/E**((((SPD-TRACK(8)-MU2)/SIGMA 2)**2)/2.0))*1000.0
      PROB 2 = (1/E**((((CSE-TRACK(7)-MU3)/SIGMA 3)**2)/2.0))*1000.0
      PROB 3 = ((PROB 1 + PROB 2)/2)
      TR LIST(J,2) = PROB 3
      TR VEL(J,3) =  CSE
      TR VEL(J,4) =  SPD
      P1 LIST(L,I) = TR LIST(1,1) * N12  + TR LIST(J,2)
      J = J + 1
  202 CONTINUE
C
```

```
C     HAVING CHECKED THIS TRACK AGAINST ALL NEW DATA, WRITE
C     TR LIST ON TAPE  2
  222 WRITE (2) TR LIST
      DO 223 I = 1, 4
      DO 223 J = 1,31
  223 TR LIST(J,I) = 0
      GO TO 2001
```

```
C
C      ALL POSSIBLE CORRELATIONS HAVE NOW BEEN LISTED.  CHECK UPDATED
C      TENTATIVE TRACKS FOR DUPLICATIONS.
C
  300 REWIND 4
      END FILE 2
      REWIND 2
C
C      NORMALIZE PROBABILITIES IN P1 LIST
C
      DO 3011 L = 1,INDEX 3
      IF(P1 LIST(L,1) .EQ. 0) 3011,3016
 3016 K = 0
      DO 3012 J = 1,29
      IF(P1 LIST(L,J) .EQ. 0) 3013,3014
 3014 N = P1 LIST(L,J) .AND. 7777B
      K = K + N
 3012 CONTINUE
      J = 30
 3013 J = J - 1
      IF ( K .EQ. 0) 3020, 3022
 3020 N = 1000/J
      DO 3021 I = 1, J
 3021 P1 LIST(L,I) = P1 LIST(L,I) .AND. 7777777777770000B .OR. N
      GO TO 3011
 3022 DO 3015 I = 1,J
      N = P1 LIST(L,I) .AND. 7777B
      N =(N *1000)/K
 3015 P1 LIST(L,I) = P1 LIST(L,I) .AND. 7777777777770000B .OR. N
 3011 CONTINUE
      NEW TR = 0
      ASSIGN 3017 TO NEXT
 3017 READ (2) TR LIST
      IF(EOF,2) 400,301
  301 IF ( TR LIST(2,3) .EQ. 777B)1000, 302
  302 IF (TR LIST(3,1) .EQ. 0) 320, 330
```

```
C
C     STEP 320 REPRODUCES A TRACK WHICH WAS NOT UPDATED THIS SWEEP
C     EXACTLY AS IT WAS BEFORE.
  320 IF (PROCTIME - TR LIST(1,4) .GT. DEADTIME )3017,321
  321 TRACK NR(1) = TR LIST (1,1)
      TRACK NR(2) = TR LIST(1,2)
      TRACK(3) = TR VEL(1,3)
      TRACK(4) = TR VEL(1,4)
      TRACK(5) = TR VEL(2,1)
      TRACK(6) = TR VEL(2,2)
      TRACK(7) = TR VEL(2,3)
      TRACK(8) = TR VEL(2,4)
      WRITE (3) TRACK
      GO TO 3017
C
C     STEP 330 TESTS FOR A TRACK WHICH WAS TENTATIVE LAST SWEEP
C
  330 K = TR LIST(1,1) .AND. 77B
      IF ( K .EQ. 0 ) 1000, 331
C
C     IF TRACK PREVIOUSLY TENTATIVE, COMPUTE LMAX AND STORE UNIT 4.
C
  331 PROB 1 = 0
      DO 332 J = 3,31
  334 IF (TR LIST (J,2) .GT. PROB 1) 335,332
  335 PROB 1 = TR LIST(J,2)
  332 CONTINUE
      PROB 2 = TR LIST(1,2) .AND. 77770000B
      PROB 1 =(PROB 2 /N12  * PROB 1)/1000
      TR LIST(1,2) = TR LIST(1,2) .AND. 77770000B .OR. PROB 1
      WRITE (4) TR LIST
      GO TO 3017
```

```
C
C      SUBROUTINE 1000 PRODUCES A NEW TRACK HISTORY FOR EACH
C      POSSIBLE CORRELATION IN THE TR LIST.
C
 1000 I = 0
      DO 303 J = 3,31
      IF (TR LIST(J,1) .EQ. 0) 305,304
  304 I = I + TR LIST(J,2)
  303 CONTINUE
      J = 32
  305 J = J - 1
      IF ( I .EQ. 0) 3051, 3053
 3051 I = 1000/(J-2)
      DO 3052 N = 3,J
 3052 TR LIST(N,2) = I
      GO TO 3054
 3053 DO 306 N = 3,J
  306 TR LIST(N,2) = (TR LIST(N,2) * 1000)/ I
 3054 DO 307 N = 3,J
      PROB 1 = 1000 - TR LIST(N,2)
      L = TR LIST(N,1)
      DO 308 K = 1,29
      IF(P1 LIST(L,K)/ N12 .EQ. TR LIST(1,1))309,308
  308 CONTINUE
      PRINT 3101
 3101 FORMAT(1X, 12HFAULT AT 306)
      STOP
```

```
 309 PROB 2 = P1 LIST(L,K) .AND. 7777B
     PROB 2 = 1000 - PROB 2
     TIME 1 = NEW DATA(L,1) - TR VEL(1,4)
     PROB = TIME 1 * COEFF 4 * 1000.0
     PROB 3 = PROB
     DENOM = E**(SIGMA T * TIME 1)
     IF ( DENOM .EQ. 0.0 ) 3093, 3094
3093 PROB = 1000.0
     GO TO 3095
3094 PROB = ( 1 - (1/DENOM)) * 1000.0
3095 PROB 4 = PROB
3091 TRACK NR(1) = TR LIST(1,1) .AND. 77777700B
     TRACK NR(2) = (PROB 1 * PROB 2)/1000 + (PROB 1 * PROB 3)/1000 +
    1  (PROB 2 * PROB 4)/1000 + (PROB 3 * PROB 4)/1000
     TRACK NR(2) = 1000 - TRACK NR(2)
     IF (TRACK NR(2) .LT. 0) 3097, 3098
3097 TRACK NR(2) = 0
3098 IF (NEW TR .EQ. 0) 3092, 3096
3096 TRACK NR(1) = NEW TR
3092 TRACK NR(1) = TRACK NR(1)   +(J- N + 1)
     TRACK NR(2) = TRACK NR(2) * N12 + PROB 4
     TRACK (3) = TR VEL(1,3)
     TRACK (4) = NEW DATA(L,1)
     TRACK (5)= NEW DATA(L,2)
     TRACK (6)= NEW DATA(L,3)
     TRACK (7)= TR VEL(N,3)
     TRACK (8)= TR VEL(N,4)
     IF( J .EQ. 3) 310,311
 310 TRACK NR(1) = TRACK NR(1) .AND. 77777700B
 311 WRITE (3) TRACK
 307 CONTINUE
     GO TO NEXT
```

```
C
C     ALL TENTATIVE TRACKS ARE NOW ON UNIT 4. ELIMINATE DUPLICATES
C
  400 END FILE 4
      WRITE(4) OLD DATA
      REWIND 4
      REWIND 2
      IF ( INDEX O .EQ. 0 ) 4002, 4003
 4003 DO 4001 I = 1,INDEX O
 4001 DATA(I,1) = 0
 4002 NN = 1
      II = 0
      MM = 1
      DO 4004 I = 1,500
 4004 DELETE(I) = 0
  420 READ (4) TR LIST
      IF(EOF, 4) 500, 402
  402 DO 403 I = 1,NN
      IF(DATA(I,1) .EQ. TR LIST(1,1)) 420, 403
  403 CONTINUE
      DO 4031 I = 1,MM
      IF ( DELETE(I) .EQ. TR LIST(1,1)) 420, 4031
 4031 CONTINUE
 4021 TRACK NR(1) = TR LIST(1,1)
      TRACK NR(2) = TR LIST (1,2) .AND. 7777B
      TRACK (4) = TR VEL (1,4)
      TRACK (5) = TR VEL (2,1)
      TRACK (6) = TR VEL(2,2)
      I = TRACK NR(1) .AND. 77B
```

```
      DO 405 J = 1,I
      READ (4) TR LIST
  405 II = II + 1
      IF (EOF,4) 450,406
  406 IF (TRACK(4) .EQ. TR VEL(1,4) .AND. TRACK(5) .EQ. TR VEL(2,1)
     1  .AND. TRACK(6) .EQ. TR VEL(2,2)) 408, 410
C
C     406 DETERMINES THAT TRACKS ARE DUPLICATE. IF YES, DECIDE WHICH
C     MOST LIKELY.
C
  408 TRACK NR(7) = TR LIST(1,2) .AND. 7777B
      IF ( TRACK NR(7) .GT. TRACK NR(2)) 4101, 4100
C
C     TRACK JUST READ IN IS GREATER. ELIMINATE FIRST ONE AND CONTINUE.
C     IF NOT, CHECK NEXT TRACK
C
 4101 DELETE(MM) = TRACK NR(1)
      MM = MM + 1
      GO TO 4021
 4100 DELETE(MM) = TR LIST(1,1)
      MM = MM + 1
  410 READ (4) TR LIST
      II = II +1
      IF (EOF,4) 450,406
```

```
C
C     HAVING SEARCHED ENTIRE FILE, THE TRACK NOW IN TRACK NR(1) IS
C     TO BE RETAINED
C
  450 DATA(NN,1) = TRACK NR(1)
      DATA(NN,2) = TRACK NR(2)
      NN = NN + 1
      IF (II .EQ. 0) 500, 451
  451 DO 452 I = 1, II
  452 BACKSPACE 4
      II = 0
      GO TO 420
C
C     LIST DATA CONTAINS ALL TRACK NRS TO BE RETAINED. WHERE THERE ARE
C     TWO FORKS OF THE SAME TRACK STILL TO BE RETAINED, RENUMBER THE
C     LEAST LIKELY AND ESTABLISH AS NEW TRACK.
C
  500 REWIND 4
      DO 501 I=1,NN
  501 DATA(I,3) = 0
      DO 502 I = 1,NN
      IF(DATA(I,3) .EQ. 0) 503, 502
  503 J = I+1
      IF (J .GT. NN) 502, 504
  504 TRACK NR(1) = DATA(I,1)/64
      DO 505 K = J,NN
      IF(DATA(K,1)/64  .EQ. TRACK NR(1))  506, 505
  506 IF(DATA(K,2)  .GT. DATA(I,2)) 507, 508
  507 DATA(I,3) = NEXT TN * 64
      NEXT TN = NEXT TN + 1
      NEXT TN = NEXT TN .AND. 77777B
      IF ( NEXT TN .EQ. 0 ) 5071, 502
```

```
 5071 NEXT TN = 1
      GO TO 502
  508 DATA(K,3) = NEXT TN * 64
      NEXT TN = NEXT TN + 1
      NEXT TN = NEXT TN .AND. 77777B
  505 CONTINUE
  502 CONTINUE
C
C     TRACKS ON UNIT 4 WHICH ARE TO BE RETAINED CAN BE DETERMINED FROM
C     DATA(I,1). THOSE WITH NEW TRACK DESIGNATIONS ARE DETERMINED BY
C     REFERENCE TO DATA(I,3)
C
      ASSIGN 600 TO NEXT
  600 NEW TR = 0
      READ (4) TR LIST
      IF(EOF,4) 700,601
  601 DO 602 I = 1,NN
      IF (DATA(I,1) .EQ. TR LIST(1,1)) 603,602
  602 CONTINUE
C
C     THIS TRACK TO BE DISCARDED. READ NEXT TRACK.
C
      GO TO 600
  603 IF(DATA(I,3) .GT. 0) 604,1000
C
C     TRACK DESIGNATION CHANGED. INSERT NEW TR NO.
C
  604 NEW TR  = DATA(I,3)
  605 GO TO 1000
```

```
C
C     TAPE 3 NOW CONTAINS ALL TRACKS IN THE SYSTEM
C
C     RECALL OLD DATA AND DISCARD DEAD POINTS
C
  700 READ (4) OLD DATA
      END FILE 3
      REWIND 3
      I = 1
      IF ( INDEX O .EQ. 0 ) 711, 7002
 7002 DO 701 I = 1, INDEX O
      IF ( OLD DATA(I,1) .EQ. 0.0) 701, 7001
 7001 IF(PROCTIME - OLD DATA(I,1) .GT. DEAD TIME) 702,701
  702 OLD DATA(I,1) = 0.0
  701 CONTINUE
C
C     INSERT UNCORRELATED NEW DATA IN OLD DATA LIST.
C
      DO 710 I = 1, INDEX O
      IF(OLD DATA(I,1) .EQ. 0) 711,710
  710 CONTINUE
  711 DO 713 J = 1,INDEX 3
      IF(P1 LIST(J,1) .EQ. 0) 712, 713
  712 OLD DATA(I,1) = NEW DATA(J,1)
      OLD DATA(I,2) = NEW DATA(J,2)
      OLD DATA(I,3) = NEW DATA(J,3)
      K=I
      DO 714 I = K,500
      IF(OLD DATA(I,1) .EQ. 0) 713, 714
  714 CONTINUE
```

```
      N = 714
      PRINT 715 ,N
  715 FORMAT(1X,  9HFAULT AT , 3I)
      GO TO 800
  713 CONTINUE
      IF(I .LT. INDEX O) 717, 800
  717 DO 718 N = I, INDEX O
      IF (OLD DATA(N,1) .EQ. 0.0) 719, 718
  719 DO 720 K = N,INDEX O
      IF (OLD DATA(K,1) .EQ. 0.0) 720, 721
  721 OLD DATA(N,1) = OLD DATA(K,1)
      OLD DATA(N,2) = OLD DATA(K,2)
      OLD DATA(N,3) = OLD DATA(K,3)
      OLD DATA(K,1) = 0.0
      OLD DATA(K,2) = 0.0
      OLD DATA(K,3) = 0.0
      GO TO 718
  720 CONTINUE
      GO TO 800
  718 CONTINUE
```

```
C
C     PREPARE NEXT PERMANENT RECORD AND PRINT RESULTS. A KEY STOP IS
C     PROVIDED HERE IN CASE A NEW TAPE IS DESIRED FOR PERMANENT RECORD
C
  800 IF (SENSE SWITCH 2) 801, 802
  801 PAUSE 2
  802 REWIND 4
      WRITE (4) NEXT TN
      WRITE (4) OLD DATA
      PRINT 803 , PROCTIME
  803 FORMAT(1H1//39X, 35HSEA SURVEILLANCE - PROCESSING TIME , F8.3//
     1   1X, 21HUNCORRELATED CONTACTS/
     2   5X, 4HTIME, 10X, 8HLATITUDE, 10X,  9HLONGITUDE,/ )
      ASSIGN 808 TO NEXT
      DO 804 I = 1,500
      IF( OLD DATA(I,1) .EQ. 0.0) 806, 805
  805 TIME 1 = OLD DATA(I,1)
      LAT 1 = (1.57079 - OLD DATA(I,2))* 57.295779
  807 LON 1 = OLD DATA(I,3)
      GO TO 1002
  808 PRINT 809, TIME 1, LAT 1, LON 1
  809 FORMAT(3X, F8.2, 9X, F7.3, 12X, F7.3)
  804 CONTINUE
C
C
C
  806 PRINT 810
  810 FORMAT(///, 1X, 13HACTIVE TRACKS//
     1 1X,  8HTRACK NR ,4X, 12H1ST TIME    ,15HLAST TIME      ,
     2 11HLAT         , 11HLON         , 11HCSE         ,  7HSPD    ,
     3 11HRELIABILITY//)
```

```
C
C     CALL EACH TRACK INDIVIDUALLY AND PRINT
C
      ASSIGN 812 TO NEXT
      NEW TR = 0
  815 READ (3) TRACK
      IF(EOF,3) 900, 816
  816 N = TRACK NR(1)/64
      IF ( N .EQ. NEW TR) 8163, 8161
 8161 NEW TR = N
      PRINT 8162
 8162 FORMAT ( 1X, 1H )
 8163 LAT 1 = ( 1.57079 - TRACK(5) ) * 57.295779
  811 LON 1 = TRACK(6)
      GO TO 1002
  812 CSE = TRACK(7) * 57.29578
      SPD = TRACK(8) * 3440.0
      PROB 1 = TRACK NR(2) / N12
      TR VEL(1,1)= PROB 1
      TR VEL(1,1) = TR VEL(1,1)/1000.0
      PROB 1 = TRACK NR(1)/64
      PROB 2 = TRACK NR(1) .AND. 77B
      PRINT 813, PROB 1, PROB 2, TRACK(3), TRACK(4), LAT 1, LON 1,
     1   CSE, SPD, TR VEL(1,1)
  813 FORMAT (1X, I5, 1H., I2, 4X, F8.3, 5X, F8.3, 3X, F8.3, 3X,
     1   F8.3,  4X, F7.3, 4X, F5.2, 6X, F6.4)
      WRITE (4) TRACK
C
C
```

```
      GO TO 815
  900 END FILE 4
      REWIND 4
      REWIND 3
 9000 IF(SENSE SWITCH 3) 904, 9001
  904 PAUSE 7000
      GO TO 9001
 1002 IF ( LON 1 .LT. 3.14159) 1004, 1003
 1003 LON 1 = LON1 - 6.28318
 1004 LON 1 = LON 1 * 57.295779
      GO TO NEXT
      END
```

```
  FUNCTION DEGREES(X,Y)
  IF ( Y .EQ. 1.57079 ) 3, 4
3 X = Y - X
  GO TO 2
4 IF ( X .GT. Y ) 1, 2
1 X = X - 2.0 * Y
2 DEGREES = X * 57.29578
  RETURN
  END
  SUBROUTINE CSESPD
```

```
      COMMON LAT2,LAT1,LON2,LON1,TIME2,TIME1,CSE,SPD
      COMMON B,A,C,COS LAT, QUAD, DEL LON
      TYPE REAL LAT2,LAT1,LON2,LON1
      TYPE INTEGER QUAD
      DATA (PI = 3.14159), (TWO PI = 6.28318), (PI OVER 2 = 1.57079)
      QUAD = 3
      B = LAT2 - LAT1
      DEL LON = LON2 - LON1
      F = (LAT1 + LAT2)/2.0
      IF(F .GT. PI OVER 2) 1,2
    1 COS LAT = COSF(F - PI OVER 2)
      GO TO 3
    2 COS LAT = COSF(PI OVER 2 - F)
    3 IF (DEL LON .GT.PI)4,5
    4 DEL LON = DEL LON - TWO PI
      GO TO 7
    5 IF (DEL LON .LT. -PI ) 6,7
C
    6 DEL LON = TWO PI + DEL LON
    7 A.= DEL LON * COS LAT
      C= SQRTF(A**2 + B**2)
C
      SPD = C/(TIME2  - TIME1)
      ANGLE = ACOSF(B/C)
C
      IF ( DEL LON .LT. 0.0 ) 8, 9
    8 CSE = PI + ANGLE
      RETURN
    9 CSE = PI - ANGLE
      RETURN
      END
```

```
  FUNCTION PB NORM(X)
  DIMENSION TABLE(50)
 0DATA (TABLE = .5, .5199, .5398, .5596, .5793, .5987,.6179,.6368,
 1  .6554, .6736, .6915, .7088, .7257, .7422, .7580, .7734, .7881,
 2  .8023, .8159, .8289, .8413, .8531, .8643, .8749, .8849, .8944,
 3  .9032, .9115, .9192, .9265, .9332, .9394, .9452, .9505, .9554,
 4  .9599, .9641, .9678, .9713, .9744, .9772, .9798, .9821, .9842,
 5  .9861, .9878, .9893, .9909, .9918, .9929)
  Y = X * 20
  IF (X .LT. 0.0) 1, 2
1 Y = -Y
2 I = Y
  YI = I
  I = I+1
  IF ( I .GT. 50) 3, 4
3 Y =1.0
  GO TO 5
4 Y = ((TABLE(I+1) - TABLE(I))* (Y - YI))     + TABLE(I)
5 IF (X .LT. 0.0) 6, 7
6 PB NORM = 1.0 - Y
  RETURN
7 PB NORM = Y
  RETURN
  END
     END
     FINIS
-EXECUTE.
```

```
-COOP,,MCARTHUR - READOUT, I/1/O/1/S/56/57,10,1500,4.
-FTN,L,E.
C
C
C     THIS PROGRAM PREPARES AN INPUT DATA TAPE FOR THE PROBABILISTIC
C     SURVEILLANCE PROGRAM, TRACK IV.  IT SIMULATES THE TELEMETERED
C     OUTPUT WHICH MIGHT BE RECEIVED FROM A SURVEILLANCE SATELLITE.
C     THE USER SHOULD LAY OUT THE PROBLEM HE WISHES TO IMPOSE ON A
C     POSITION PLOTTING SHEET.  FROM THIS PLOT PUNCHED CARDS MAY
C     BE PREPARED TO BE PROCESSED BY THIS PROGRAM.  THE FORM OF THE CARD IS
C
C  TIME      LATITUDE  LONGITUDE
C
C     TIME IS IN COLUMNS 1 TO 10.  IT REPRESENTS HOURS AND MAY BE
C     ACCURATE TO THE NEAREST THOUSANDTH OF AN HOUR.  TIME MUST ALWAYS
C     BE GREATER THAN ONE HOUR SINCE TIME ZERO AND TIME ONE ARE USED
C     AS END-OF-READOUT AND END-OF-PROBLEM FLAGS RESPECTIVELY.
C
C     LATITUDE AND LONGITUDE ARE EXPRESSED IN DEGREES AND MINUTES
C     WITH MINUTES SEPARATED FROM DEGREES BY A PERIOD.  THERE SHOULD
C     BE NO SPACES IN EITHER EXPRESSION BECAUSE THIS PROGRAM READS
C     THE EXPRESSIONS AS FLOATING POINT NUMBERS IN F FORMAT THEN
C     CHANGES MINUTES TO FRACTIONAL DEGREES BY CORRECTING THE
C     FRACTION PART OF THE FLOATING POINT NUMBER.  LATITUDE IS
C     PUNCHED IN COLUMNS 11 TO 20 AND LONGITUDE IN COLUMNS 21 TO 30.
```

```
C
C     THE FOLLOWING CARD IS AN EXAMPLE OF THE INPUT FORMAT.
C
C  35.96     41.32   -176.30
C
C     THE POSITION REPORT INDICATED ON THIS CARD IS
C
C              TIME - 35.96
C
C              LATITUDE - 41 DEGREES AND 32 MINUTES NORTH
C
C              LONGITUDE - 176 DEGREES AND 30 MINUTES WEST
C
C     BY CONVENTION, EAST LONGITUDE IS POSITIVE AND WEST IS NEGATIVE.
C     SIMILARLY, NORTH LATIDUDE IS POSITIVE, SOUTH NEGATIVE.
C
C     TO INDICATE THE END OF A READOUT, INSERT A CARD WITH ALL OF THE
C     THREE FIELDS EQUAL TO 0.0.  TO INDICATE THE END OF A
C     PROBLEM, SET EACH FIELD TO 1.0.
C
C
```

```
      PROGRAM READOUT
      DIMENSION DATA(100,3)
      K=100
    1 DO 2 I = 1,K
      DO 2 J = 1,3
    2 DATA(I,J) = 0.0
      DO 10 I = 1,100
      READ 11,DATA(I,1),DATA(I,2), DATA(I,3)
   11 FORMAT(F10.5,F10.5,F10.5)
      IF(DATA(I,1) .EQ. 0.0)12,13
   12 WRITE (1) DATA
      K = I
      GO TO 1
C
   13 IF(DATA(I,1) .EQ. 1.0) 14, 17
   14 IF(DATA(1,1) .GT. 0.0) 15,16
   15 DATA(I,1)=0
      WRITE (1) DATA
   16 END FILE 1
      REWIND 1
  110 STOP
C
   17 X = ABSF(DATA(I,2))
      N=X
      FRACTION= X - N
      FRACTION= (FRACTION * 100.0)/60.0
      IF(DATA(I,2) .LT. 0.0) 181, 182
  181 DATA(I,2) = -(N + FRACTION)
      GO TO 183
```

```
  182 DATA(I,2) = N + FRACTION
  183 X = ABSF(DATA(I,3))
      N = X
      FRACTION = X - N
      FRACTION = (FRACTION * 100.0)/60.0
      IF(DATA(I,3) .LT. 0.0) 184,185
  184 DATA(I,3) = -(N + FRACTION)
      GO TO 186
  185 DATA(I,3) = N + FRACTION
C
  186 DATA(I,2) = ( 90.0 - DATA(I,2))/57.295779
      IF(DATA(I,3) .LT. 0.0) 18,19
   18 DATA(I,3) = 360.0+ DATA(I,3)
   19 DATA(I,3) = DATA(I,3)/57.295779
C
   10 CONTINUE
      PRINT 101
  101 FORMAT(1X 5HFAULT)
      STOP
      END
         END
         FINIS
-EXECUTE.
```

APPENDIX IV

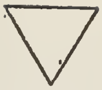
FLOW CHARTS FOR THE PROBABILISTIC MODEL

The flow charts in the following pages are intended to give the reader a general picture of the manner in which the logic of the probabilistic model was implemented in TRACK IV. Detailed flow charts may be obtained by contacting the Operations Analysis Department of the U. S. Naval Postgraduate School.

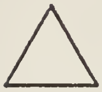
The quantity L_{max} which appears in the flow charts is defined as the probability that a tentative track A.n established on sweep i is the true extension of track A in view of the possible extensions determined on sweep i+1. L_{max} is computed as the maximum $p_{s\theta}$ over all possible extensions of track A.n multiplied by the track reliability of track A.n computed on sweep i.

L_{max} is used to eliminate tentative extensions established on sweep i which are duplicates of tentative extensions for other tracks established on sweep i. The duplicate with the highest L_{max} is retained. L_{max} is also used to determine which branch of a split track should retain the identity of the track and which should be redesignated. The branch with the highest L_{max} retains the former designation and all others are redesignated.

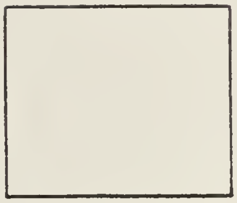
FLOWCHART SYMBOLS



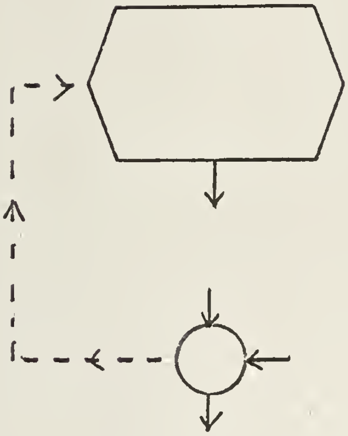
start



stop

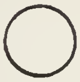


computation or replacement procedure

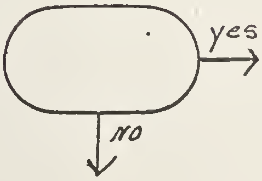


DO loop

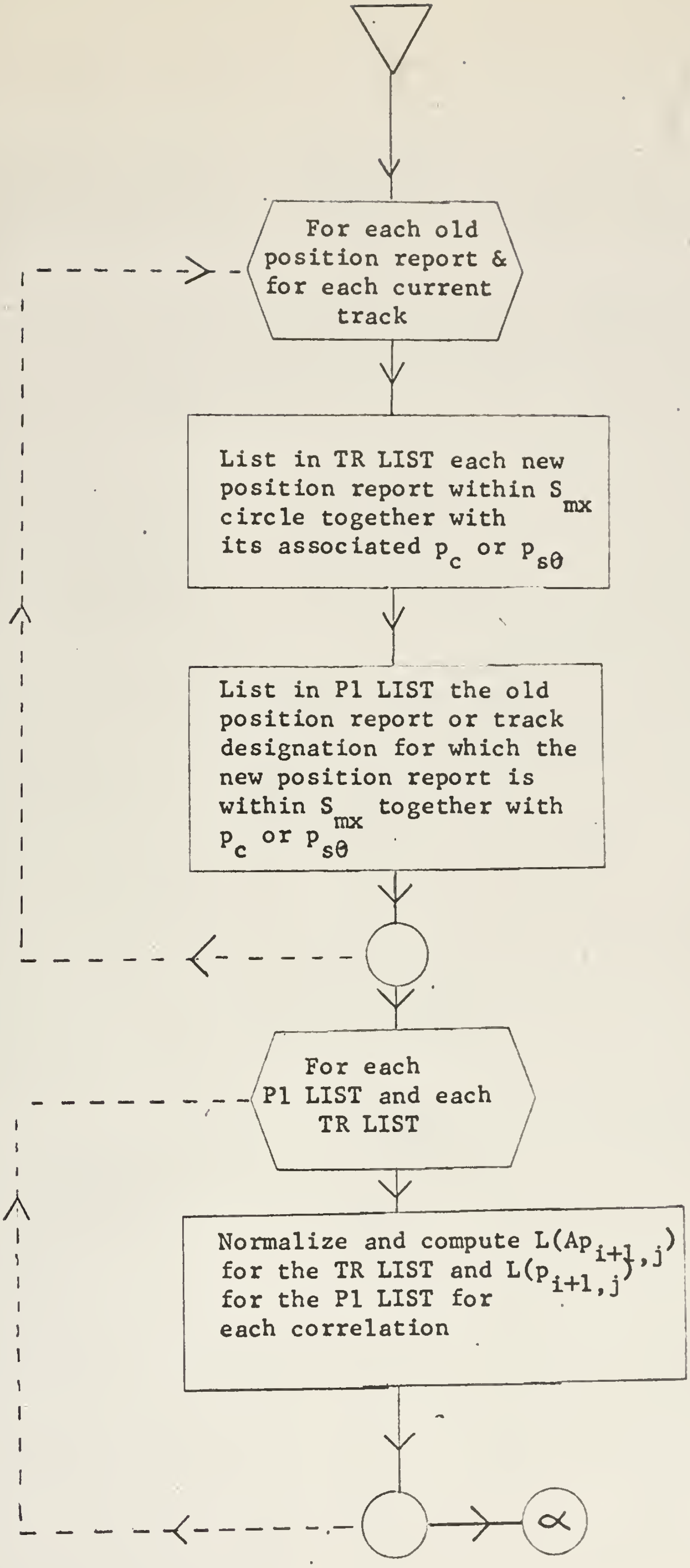
termination of DO loop or junction of two or more branches of the program

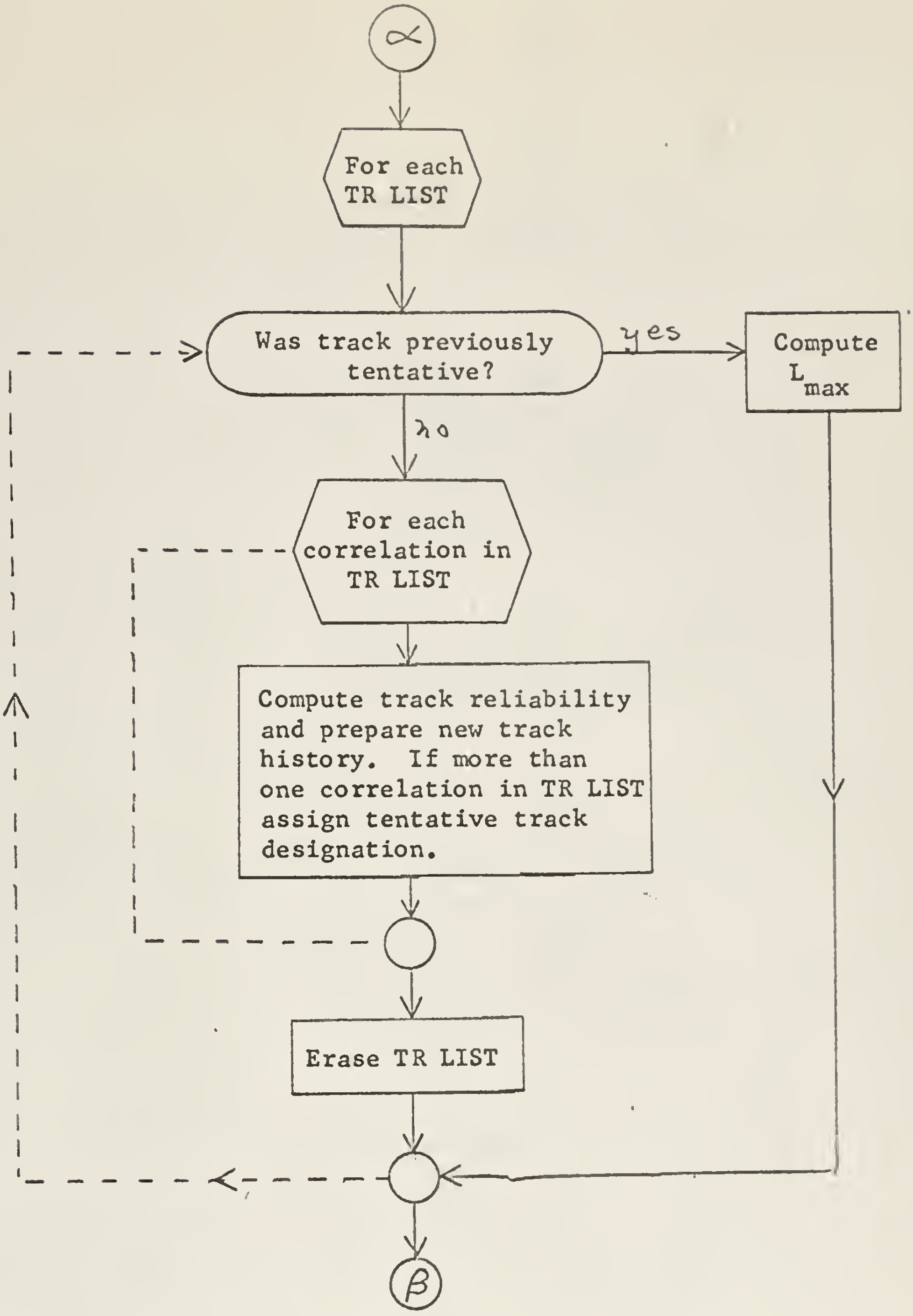


link between pages

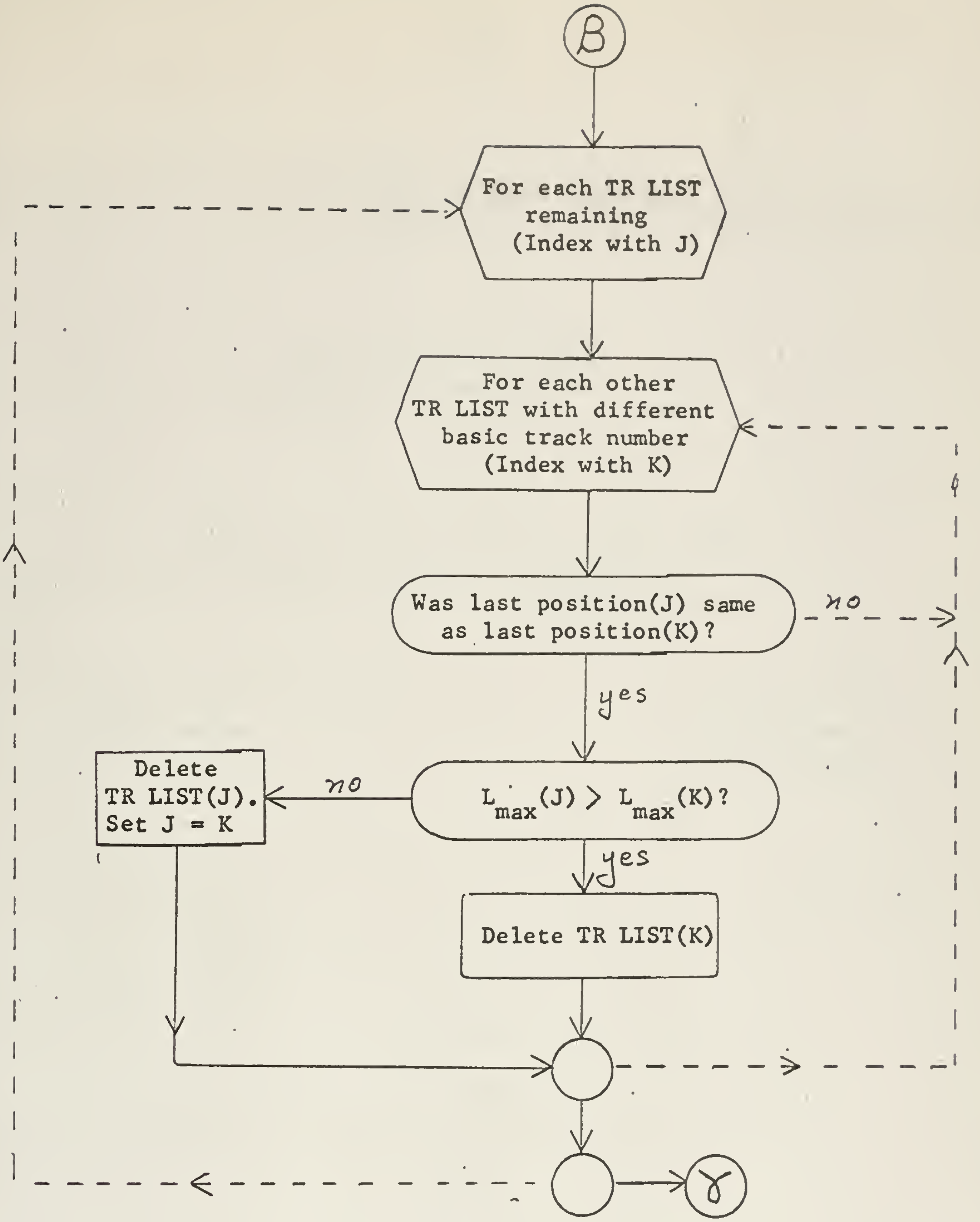


conditional GO TO

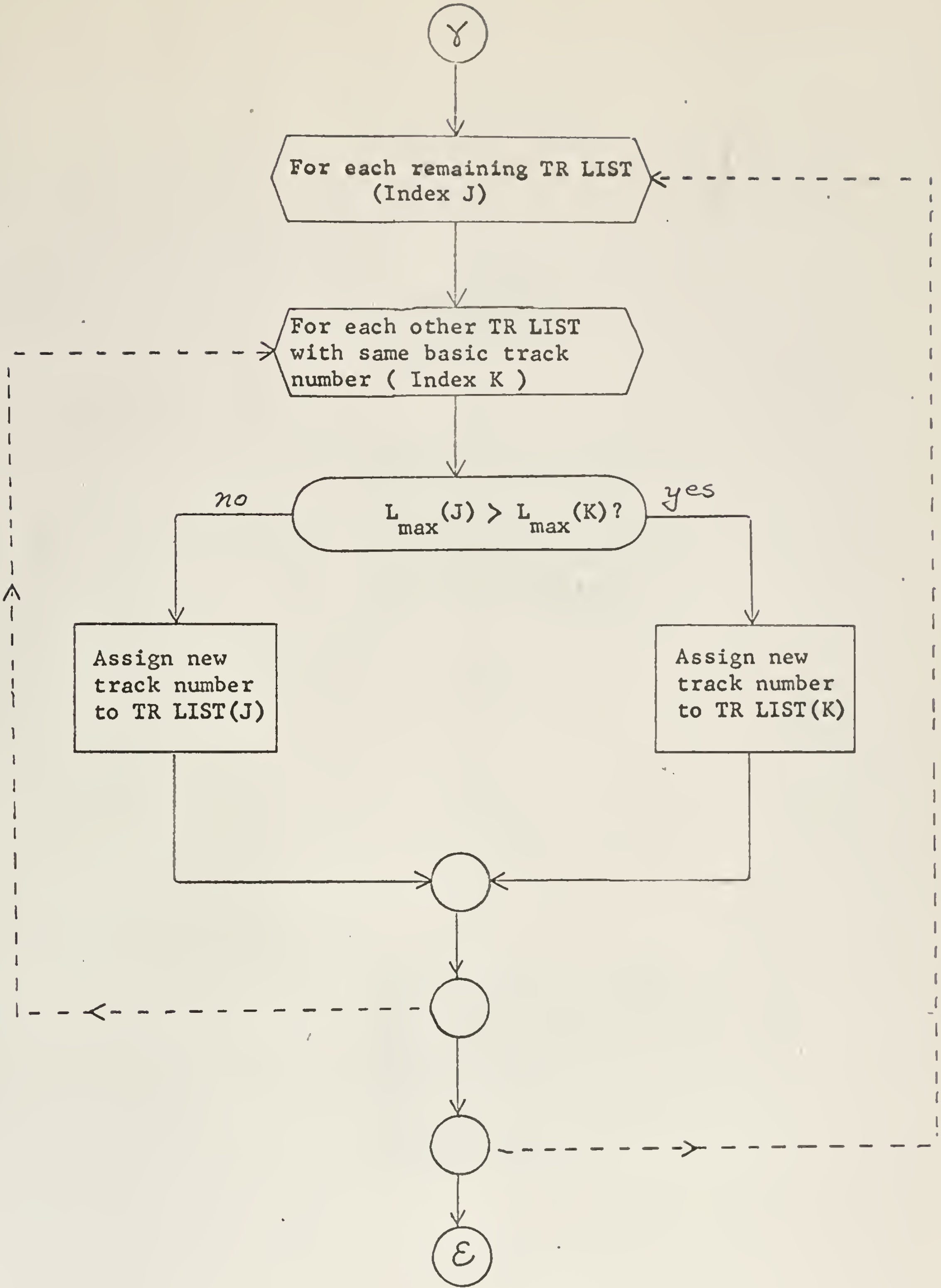

For each old position report & for each current track
List in TR LIST each new position report within S_{mx} circle together with its associated p_c or $p_{s\theta}$
List in P1 LIST the old position report or track designation for which the new position report is within S_{mx} together with p_c or $p_{s\theta}$
For each P1 LIST and each TR LIST
Normalize and compute $L(Ap_{i+1,j})$ for the TR LIST and $L(p_{i+1,j})$ for the P1 LIST for each correlation
α

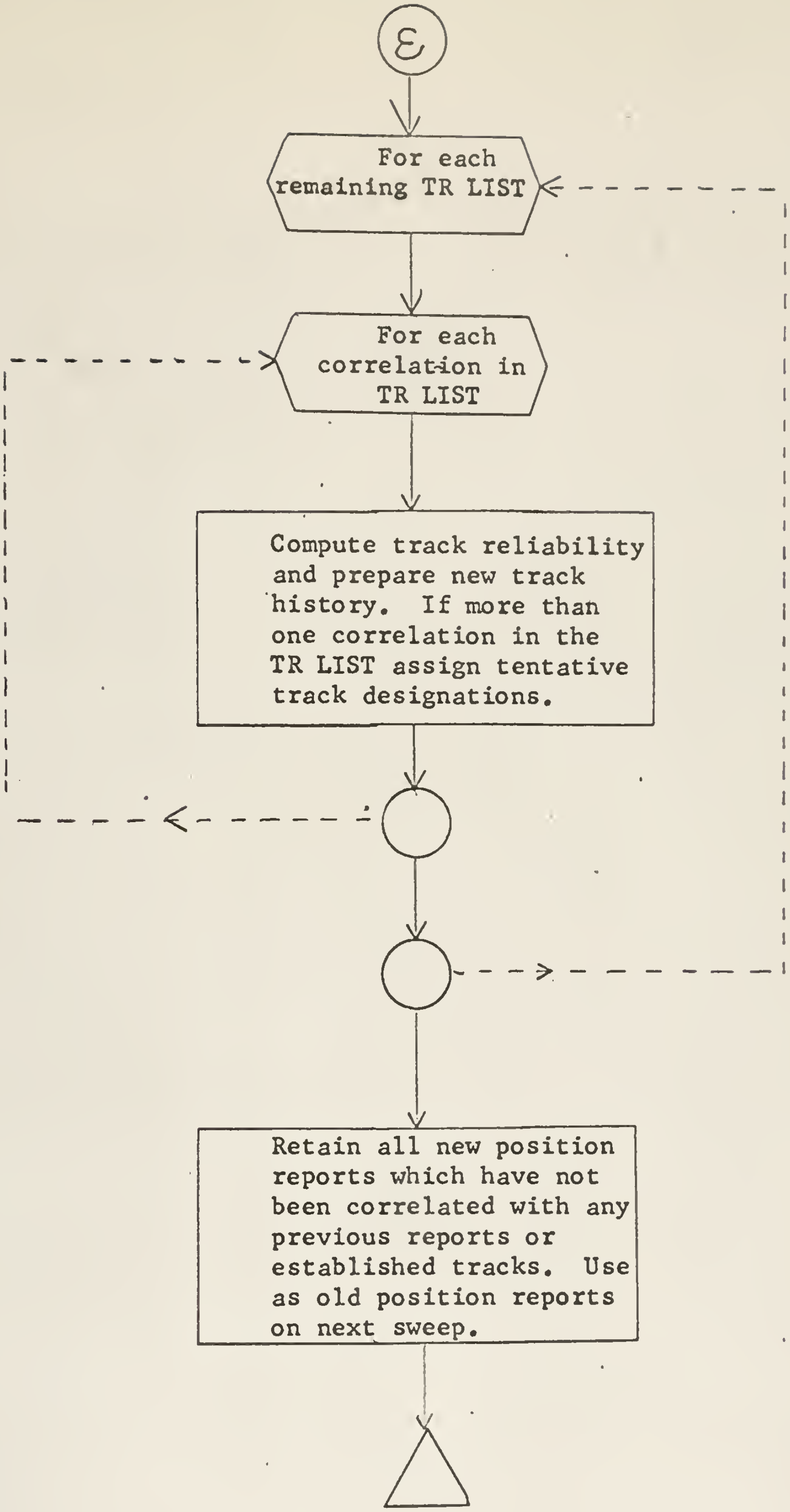


α
For each TR LIST
Was track previously tentative?
yes
Compute L_{max}
no
For each correlation in TR LIST
Compute track reliability and prepare new track history. If more than one correlation in TR LIST assign tentative track designation.
Erase TR LIST
β


B
For each TR LIST remaining (Index with J)
For each other TR LIST with different basic track number (Index with K)
Was last position(J) same as last position(K)?
no
yes
Delete TR LIST(J). Set J = K
no
$L_{max}(J) > L_{max}(K)$?
yes
Delete TR LIST(K)
γ

Note: All duplicate tentative tracks have been eliminated.


γ
For each remaining TR LIST (Index J)
For each other TR LIST with same basic track number (Index K)
no
$L_{max}(J) > L_{max}(K)$?
yes
Assign new track number to TR LIST(J)
Assign new track number to TR LIST(K)
ε


E
For each remaining TR LIST
For each correlation in TR LIST
Compute track reliability and prepare new track history. If more than one correlation in the TR LIST assign tentative track designations.
Retain all new position reports which have not been correlated with any previous reports or established tracks. Use as old position reports on next sweep.

thesM135
Correlation of ship position reports gat
3 2768 001 88683 1
DUDLEY KNOX LIBRARY